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COLLEGE STATION, TEXAS

CIRCULATION OVER THE CONTINENTAL MARGIN OF THE NORTHEAST GULF OF MEXICO

R. D. GAUL

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TEXAS A&M UNIVERSITY
Department of Oceanography
College Station, Texas

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Project 286-D was sponsored by the Office of Naval Research under contract Nonr 2119(4). The work reported herein is of a preliminary nature and the results are not necessarily in final form.

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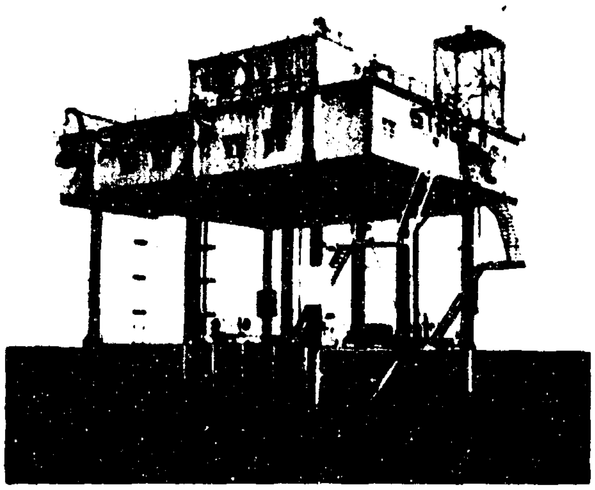

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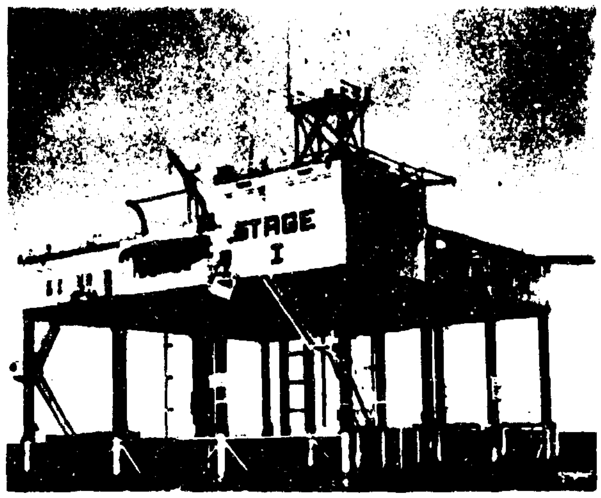

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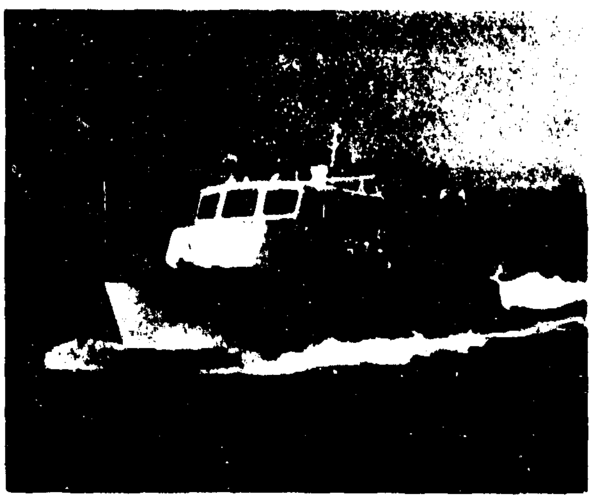
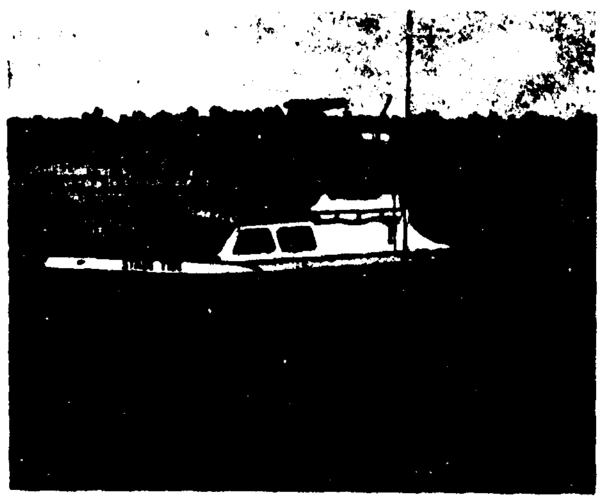


R/V DROGUE OF 19 METERS LENGTH



R/V STAGE TIDE OF 13 METERS LENGTH

FRONTISPIECE. Platforms and vessels used for acquisition of environmental data in the northeast Gulf of Mexico.

PREFACE

This report is a preliminary and somewhat abbreviated version of a dissertation to be submitted as partial requirement for a doctor of philosophy degree from Texas A&M University. The work has been supported wholly by the Office of Naval Research as a part of the air-sea environmental research program with field facilities at Panama City, Florida. The program was initiated by the Department of Oceanography at Texas A&M University in May 1961 and is being terminated in August 1966. A summary of the program is given in a final report (Gaul, 1966).

ABSTRACT

The quasi-steady ocean circulation over the continental margin of the northeast Gulf of Mexico has been delineated on the basis of three years of hydrographic and direct current observations. Observations were made by a wide range of techniques at two fixed platforms in the nearshore region off Panama City, Florida, and from small vessels during periodic surveys conducted over a larger area. Special attention has been given to the accuracy of measurements and to the temporal and spatial distribution of sampling relative to scales of observed circulatory phenomena.

Evidence is presented for a close coupling between circulation over the continental margin and that in deeper water. The "loop" current, that transports water into the Gulf from the Yucatan Channel, is identified as far north as the edge of the northeast continental slope and lateral mixing with waters over the continental margin is verified. It is suggested that the circulation in deep water is the main driving influence for circulation over the continental margin, especially below the seasonal thermocline.

A close relationship between vertical stratification and currents observed in the northeast Gulf is noted. There is a net transport onshore of water below the thermocline that maintains a sharp density stratification over the entire shelf and into water depths of a few meters during the spring and summer months. The stratification gradually diminishes during the fall and the typical winter situation is a nearly homogeneous water mass over the shelf that is an extension of the surface layer further offshore. These seasonal changes in hydrography are reflected in the circulation but are difficult to evaluate quantitatively because of comparable nonseasonal changes.

Current velocities associated with the internal tide were found to be significant only over the continental shelf. Direct

current measurements over the continental slope revealed currents of tidal period having speeds of a few tenths of a meter per second whereas steady currents in the same general region were several times larger. A barotropic shear flow was evident from these measurements; no significant baroclinic flow was detected. Internal tide currents over the continental shelf are comparable to quasi-steady currents in the presence of sharp stratification. However, there is the possibility that these currents may be under the main influence of combined diurnal tide and inertia rotation modified by friction at the bottom and between the two layers.

Flow over the continental margin is modified markedly by ocean bottom topography. De Soto Canyon, the most prominent single bathymetric feature, appears to have a dominant influence on replenishment of water in the lower layer over the shelf. A zone of transition in hydrography and currents has been noted along the break between shelf and slope, especially during spring months when stratification over the shelf is incipient.

Mesoscale eddies have been observed over the continental slope. Two remarkable aspects of these vortices are that they were found intermittently and that both cyclonic and anticyclonic rotation have been observed. It remains unknown as to whether or not the eddies build up and decay locally or are part of a system of vortices (that might be generated by lateral shear between inshore and offshore mesoscale motion) that travel along the continental slope.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure		Page

LIST OF SYMBOLS AND ABBREVIATIONS

a,b,c	Empirical coefficients in relation for salinity as a function of conductivity ratio.
D	Geopotential (dynamic height) anomaly (dynamic meters).
f.s.	Full scale (calibrated range of a transducer).
G	Conductivity.
h	Vertical separation between probes (m).
K_G	Conductivity coefficient
K_R	Conductivity ratio coefficient.
L	Horizontal distance between two positions of known geopotential anomaly (kilometers).
m	Meter(s).
mps	Meters per second.
p	Pressure (decibars).
R	Conductivity ratio.
S	Salinity (‰).
S*	Uncorrected or indicated salinity from STD salinity sensor (‰).
t	Time (seconds; hours).
T	Temperature (°C).
u	Average geostrophic current (mps).
V	Instrument descent rate (mps).
z	Vertical coordinate (m).
α, β, γ	Empirical coefficients in relation for conductivity ratio as a function of salinity.
α_{stp}	Specific volume; reciprocal of density as a function of salinity, temperature and pressure.
δ_{st}	Thermosteric anomaly; function of density at atmospheric pressure.
ρ_{st}	Density of water as a function of salinity and temperature only.
σ_t	Sigma-t; function of density at atmospheric pressure.
τ	Instrument descent rate (mps).

ϕ	Latitude (degrees).
ω	Angular speed of earth rotation = 0.729×10^{-4} radians per second.
°C	Degrees centigrade.
%	Per cent.
‰	Parts per thousand.

I. INTRODUCTION

This report sets forth a composite picture of the ocean circulation over the continental shelf and slope of the northeast Gulf of Mexico as inferred from hydrographic and current observations made during 1963-1966. Based on these observations, an attempt is made to define the dominant circulatory features and to assess temporal variations due to tides and seasonal changes. The region of study (Figure I-1) extends from the Mississippi delta to Cape San Blas and offshore to about the 2000 meter depth contour.

Sweitzer (1898) concluded from sailing logs and scattered observations dating back to 1663 that the current system in the Gulf of Mexico could be separated into "deep-stream currents" that entered through the Yucatan Channel and "littoral-drift currents" that moved along the coast. The deep-stream currents were presumed either to move around Cuba and directly out the Florida Straits or to be directed northward towards the center of the Gulf and then spread out in all directions. Which of the two situations prevailed was supposed to be dependent on "planetary conditions" and atmospheric pressure distribution over the Gulf and southeastern United States. The littoral drift currents were considered to be wholly wind driven and move from the Mexican and Florida coasts to a convergence region off Galveston, Texas. Haupt (1898) countered the above description with an heuristic analogy to rack and pinions suggesting the existence of two closed gyres of opposite rotation in the west Gulf and a dual current in the east Gulf that turns eastward around Cuba as well as along the continental boundary east of the Mississippi delta before rejoining and leaving through the Straits of Florida. The contention that the littoral flow was northward along the Texas coast towards a convergence off Galveston also was contested by several investigators.

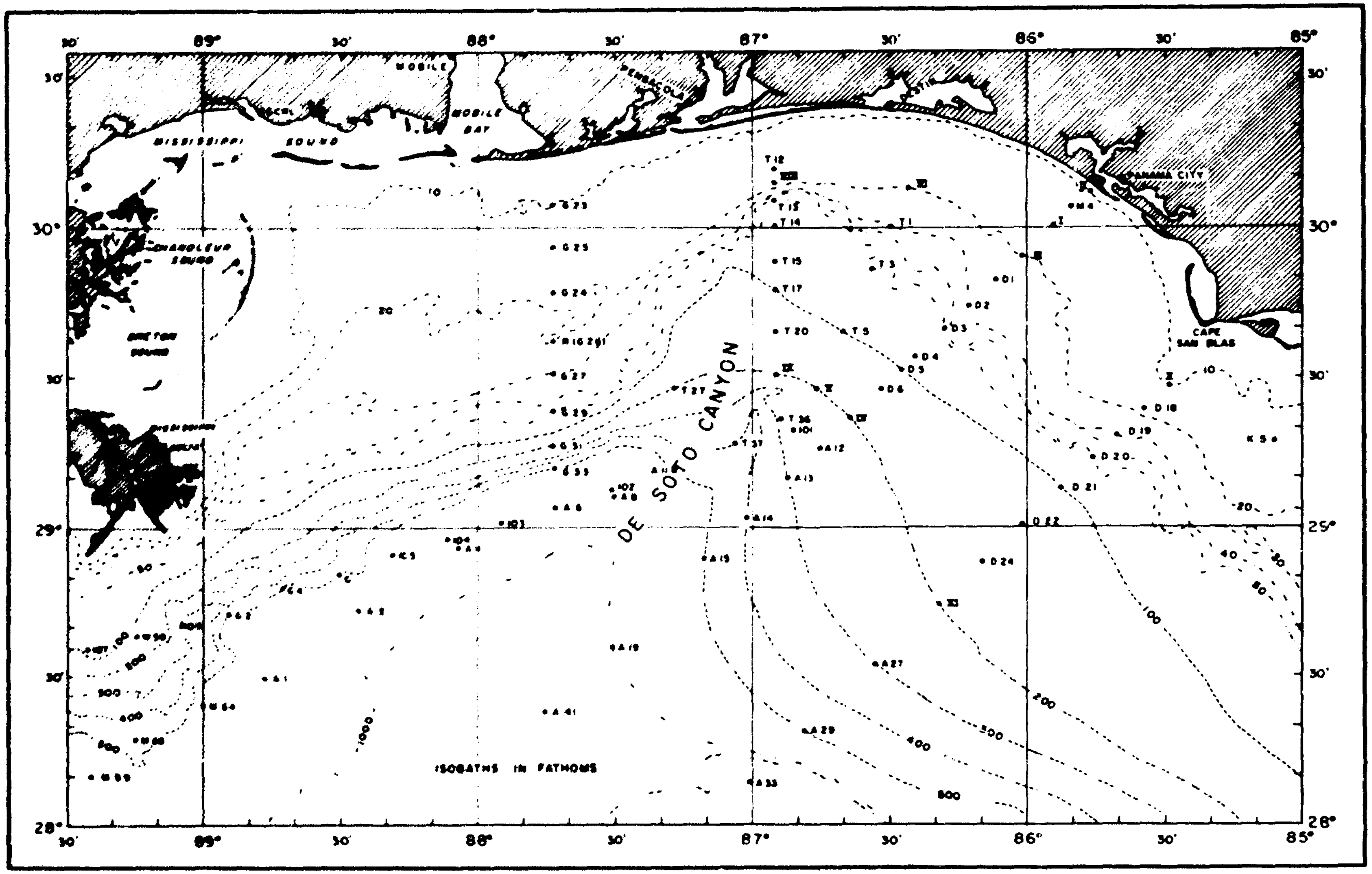


FIGURE I-1. Chart of northeast Gulf of Mexico showing locations of key hydrographic measurement stations.

Sweitzer's closure to the discussions concluded with a quotation from Professor Mendenhall, Chief of the Coast Survey, "Nothing positive is known of the currents of the Gulf of Mexico."

Based on observations in the Gulf and Florida Straits by the Dana in 1922 and the Mabel Taylor in 1932, Parr (1935) concluded that the flow through the Yucatan Channel proceeded directly outward through the Straits of Florida without significant interaction with waters within the Gulf. Leipper (1954) suggested that data available to Parr were inadequate and presented streamline patterns inferred from pilot charts issued by the U.S. Navy Hydrographic Office that indicated intrusion and spreading of Yucatan inflow in the general manner suggested by Haupt (1898) except that well defined gyres were absent in the west Gulf.

An analysis by Austin (1955) of geostrophic currents inferred from hydrographic data collected from 1951 to 1954 indicated that the circulation in the upper 1000 meters of the east Gulf was intimately coupled with the inflow through the Yucatan Channel. A complex system of eddies was indicated within an enclosed loop of the general nature suggested by Haupt (1898). Duxbury (1962) combined all data from cruises by the Department of Oceanography and Meteorology at the A&M College of Texas to obtain dynamic topography relative to various levels in the upper 1000 meters. The results indicated systems of eddies somewhat similar to the main features noted by Austin (1955). The inconsistent time and space distributions of sampling, the degree of uncertainty in the hydrographic measurements and the use of arbitrarily selected reference levels make doubtful any conclusions as to the relation of these two analyses to actual Gulf circulation, either at a given time or averaged over a long period. However, it seems clear that a much greater extension into the Gulf of the flow through the Yucatan Channel exists than envisaged by Parr (1935).

Direct measurements by Cochrane (1962; 1963) show that northward extension of Yucatan inflow is well into the Gulf. The westward intensification of the current is likened to the Gulf Stream and Kuroshio. It is also evident that seasonal (or shorter period) fluctuations of current strength and range of intrusion into the Gulf are large. Results obtained by D. F. Leipper (personal communication) in 1964-1966 by means of temperature measurements made along a variety of tracks in the Gulf indicate that flow into the Gulf tends to be concentrated in meandering ribbons of the order of 40 miles wide that enclose well defined eddies. The number and locations of these eddies vary considerably over periods of a few months or less.

A circulatory picture differing somewhat from all of those mentioned above has been suggested by Nowlin and McLellan (1967) based on hydrographic and geomagnetic electrokinetograph current measurements over a six-week period in the winter of 1962. Northward intrusion of the Yucatan current is unmistakable in dynamic topographies as well as the current measurements but the "loop" current was confined to a single well defined gyre that extended no further north than the 27th parallel, i.e., about half way from the Yucatan Channel to the Mississippi delta. An east-west ridge in the dynamic topography extended well into the east Gulf between the loop current and the Mississippi delta. A survey in June 1966 by Nowlin and Reid, which will be discussed later, shows the loop extending much further north.

Extensive drift bottle releases have been made in the east Gulf of Mexico by several investigators (Chew, Drennan and Demoran, 1962; Drennan, 1963; Gaul and Boykin, 1964 and 1965; Gaul, Boykin and Letzring, 1966; Tolbert and Salsman, 1964). Most of the releases were in the study region shown in Figure I-1. Since winds in the east Gulf typically are

light and variable over several months. it is significant that a large percentage of retrievals were from the Florida coastline between Key West and Cape Kennedy (Canaveral) whereas returns from the east Florida coast were insignificant. Average drift speeds for the earliest arrival ranged to nearly one meter per second. These results strongly suggest that the surface water (upper few meters) is transported southward by the loop current which suffers little exchange with the waters over the broad east Florida shelf. The drift bottle studies also indicate that small scale striations or shear zones exist in the surface current regime, especially over the northeast Gulf shelf, such that east and west transport occur simultaneously along the continental boundary and past the Mississippi delta. The position, intensity and orientation of these features appear to be highly variable over periods of a few weeks or less and transverse exchange may account for cases of retrievals from both east and west for a single set of releases.

Ichiye (1960) evaluated the influence of the Mississippi River outflow on Gulf hydrography and circulation. It is concluded "... that the Mississippi drainage does not spread beyond the continental shelf." However, the sparse data indicate that estuarine waters are transported along the shelf by a current directed to the east-northeast which is presumed "... to be a part of the permanent vortex in the northeastern Gulf forming at the end of loop of the Florida current ..."

Several major points of confusion and contradiction are apparent among the few significant investigations of Gulf circulation. This is to be expected in view of the obvious mismatch between distributions of sampling in relation to indicated temporal and spatial variability. The range of northward extension of flow through the Yucatan Channel remains in question as do the degrees of coupling and water exchange between the loop and surrounding waters. The intent of the investigation summarized below was to delineate the circulatory features

over the continental boundary with particular emphasis on temporal variability, spatial scales and coupling with dominant currents in the offshore region. Although emphasis was on the boundary circulation, evidence of the nature of quasi-steady circulation in the open Gulf will arise from such a study if a strong coupling exists.

II. THE OBSERVATIONAL PROGRAM

The environmental field program carried out in the northeast Gulf of Mexico from 1962 to 1966 embraced two distinctly different approaches to data acquisition. One method employed highly automated techniques for acquiring semi-continuous records from a variety of electronic transducers mounted on or in the immediate vicinity of two offshore platforms located in the nearshore region off Panama City, Florida (Figure II-1). The second approach involved use of vessels to obtain hydrographic data at selected positions (stations) distributed over the larger region shown in Figure I-1. The "fixed station" data obtained by the first method provide a means of assessing the temporal variability of the environment whereas the "survey" data are applicable mainly to assessment of spatial distributions. Salient features of the two approaches are given in the following sections.

A. Fixed Station Data

The bulk of "fixed station" data used in this study were obtained from transducers located on or near two large steel structures (platforms) rigidly imbedded in the sea floor off Panama City, Florida. One of the platforms, named Stage II and frequently identified below simply as "II," is located three kilometers offshore in a nominal water depth of 18 meters. The other platform (Stage I denoted "I") is located 20.5 kilometers offshore in a depth of 31 meters. The two platforms lie on a line approximately perpendicular to the depth contours and coast line which trend from northwest to southeast.

The Texas A&M University program initiated in 1961 to use the platforms off Panama City began successful environmental monitoring in mid-1962 at Stage I and in 1963 at Stage II. Additional specialized data that were acquired from St. Andrews

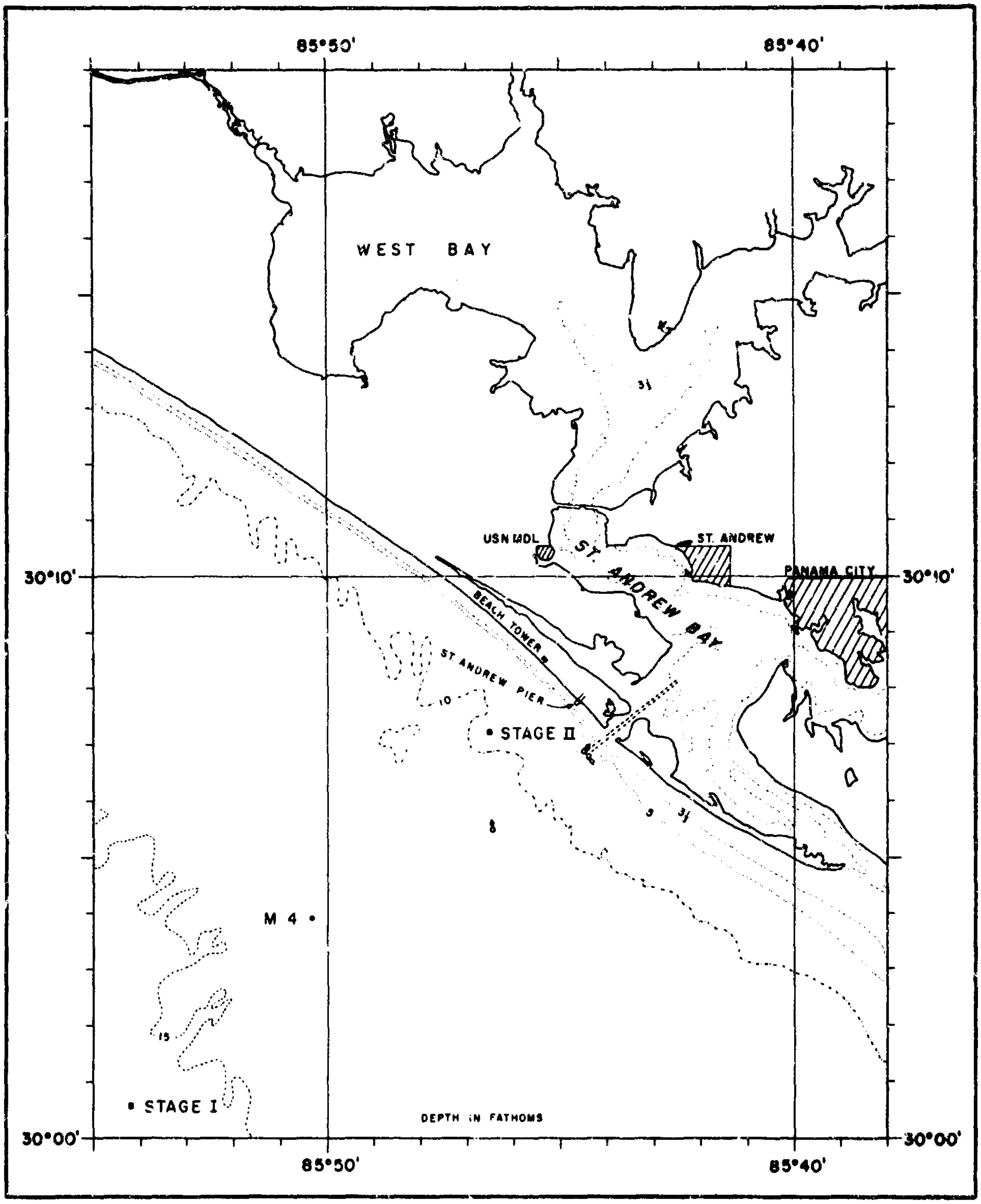


FIGURE II-1. Location chart of nearshore region off Panama City, Florida.

Pier and the Beach Tower (Figure II-1) have not been used for this study. A summary of all the data collected by the automated system is given by Kirst and McMath (1966a; 1966b). Only a small part of the fixed station data available has been drawn on for this circulation study.

1. Automated data handling. Since the automated data system has been described previously (Gaul, Kirst and McQuilken, 1963; Gaul and Kirst, 1965), the discussion below will be limited to delineation of key operational features pertinent to the data used for this circulation study. A functional block diagram of the system is given in Figure II-2.

The environmental transducers were connected by cables to a central sampling and telemetering system located on one of the platforms. The central system sampled each transducer output once per second and converted it to an eight binary digit format prior to transmission to the Beach Tower situated on the beach front. The normal coding precision of the sampling system is within the lowest order binary digit, i.e., one part in 256 or about 0.4 per cent of the full scale range of the transducer. The encoded serial data were transmitted by radio or submarine cable to a receiving and recording system at the beach tower. The most significant feature of the recording system is that by means of a pair of magnetic tape recorders under timer control, it was possible to obtain uninterrupted monitorings of the environment for indefinite periods. Uninterrupted data for periods of several days were taken frequently. Most unanticipated interruptions in the data stream were due to failures of individual transducers or electrical power components in the unattended system on the platforms.

The magnetic tape records made in the field were shipped to the Texas A&M University campus for routine reduction to a computer compatible format and permanent storage on magnetic

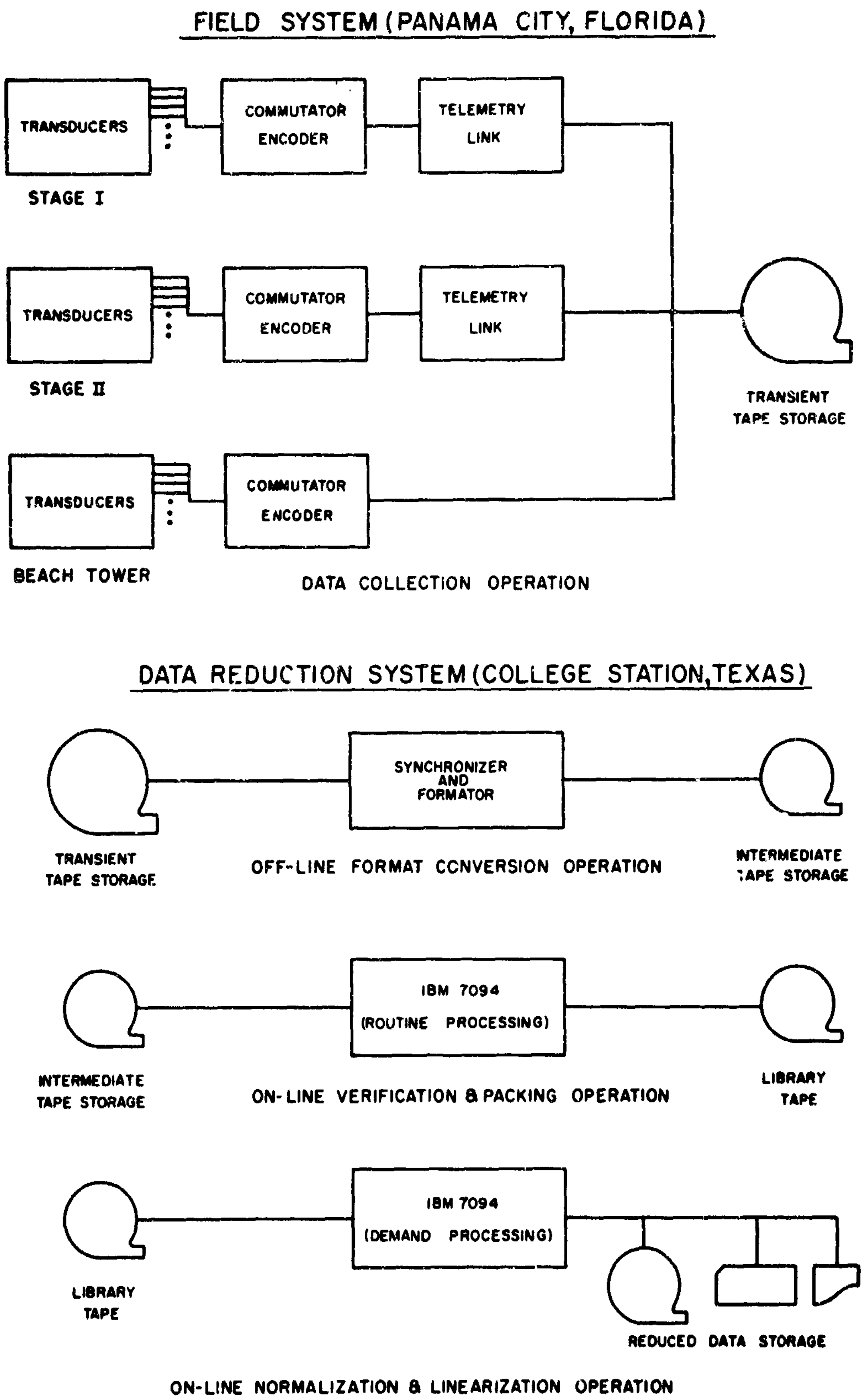


FIGURE II-2. Functional arrangement of automated data system.

tape. It is from these library tapes that data for all subsequent analyses are drawn. One notable feature of the reduction process is that parity checking techniques are employed to detect alterations of the binary sample representations that might have occurred during the course of transmission, recording or playback. Data words (samples) not fulfilling the parity requirement simply were rejected and subsequently treated as though no sample had been taken. Parity combined with other diagnostic techniques seems to have resulted in good assurance that transducer output values were accurately preserved throughout the data handling process.

2. Instrumentation. Environmental parameters and the nominal elevations at which they were monitored at the platforms are given in Table II-1. Elevations are taken positive upwards in reference to the nominal mean water level. Actual elevations of the underwater transudcers were changed from time to time but were within a few meters of the nominal depths shown in Table II-1 during periods selected for this study. Meteorological transducers were mounted on a vertical pipe atop the southwest (offshore) corner of each of the platforms at a level about seven meters above the uppermost deck (comprising one-fourth of total deck area) and 27 meters above the water surface. The underside of both platforms was 12.5 meters

TABLE II-1. Parameters measured at platforms.

Parameter	Elevation of Stage I (meters)	Elevation of Stage II (meters)
Air temperature	27	27
Wind velocity	27	27
Water level	0	0
Water temperature	-3,-6,-9,-12,-15,-18,-21,-24,-27,-30	-5,-11,-17
Current velocity	-6,-16,-30	-5,-17

above the water surface. The water level probe was located on the outboard side of the platform facing offshore and mounted on a vertical piling 0.8 meters in diameter. Underwater transducers were on a "taut wire" mooring located about 150 meters offshore from the southwest corner of the platforms.

The types and estimated absolute accuracies (after encoding, transmission and reduction) of transducers used at the platforms are given in Table II-2. A standard three cup anemometer and wind vane mounted on vertical rotational shafts and separated about one meter horizontally were used for wind velocity measurement. A thermistor mounted in the throat of a fan aspirated radiation shield was used for air temperature measurement.

TABLE II-2. Types and accuracies of automated system transducers.

Parameter	Type	Full Scale Range	Nominal Accuracy
Air temperature	Thermistor	-5 to 40°C	±0.3°C
Wind speed	Cup Anemometer	0-50 mps*	±0.5mps
Wind direction	Vane	0 to 360°M	±5°M
Water level	Resistance wire	6 or 9 m**	±0.04 or ±0.06 m
Water temperature	Resistance thermometer	8 to 33°C	±0.13°C
Current speed	Savonius rotor	0 to 3.5 mps	±0.05mps***
Current direction	Vane	0 to 360°M	±5°M

*Nominal range corresponding to 0 to 100 knots.

**Nominal total lengths of probe corresponding to 20 or 30 feet prior to middle of 1965. Midpoint of probe was placed at estimated mean water level.

***Applicable to nominal range of 0.1 to 0.5 mps.

Water level measurement was by means of a wound wire resistance system described by Ayers and Cretzler (1963) and subsequently evaluated by Gaul and Brown (1966). The water temperature probe was a platinum resistance thermometer (Hoover, 1963) with a nominal time constant of 0.3 seconds and an impregnated shield to protect the resistance coil sheath from biological fouling.

Current speed was measured with Savonius rotor current meters. An analysis of the operating characteristics of these horizontally omnidirectional rotors has been summarized by Gaul, Snodgrass and Cretzler (1963) and the specific type of meter used at Panama City is shown in Figure 2 of that publication. Rectangular vanes free to rotate about a vertical axis near the leading edge were used for independent measurement of current direction about one meter above or below the Savonius rotor. The approximate dimensions in the vertical plane of the slightly tapered vane were 0.08 meter wide and 0.17 meter long. Direction meters coaxially suspended on a taut wire mooring were internally equipped with a magnetic north direction reference. Direction measurements near the sea floor (nominally one meter above the bottom) were by means of meters rigidly mounted on a pedestal by divers after aligning a designated point on the case with magnetic north as estimated from wrist compasses. In either case, the nominal tolerance of the direction reference should be less than ±5 degrees.

Water level (tide) observations were taken at the end of St. Andrews State Park Pier, where the nominal water depth is 5 meters, during the period October 1962 - May 1966. The system was of the "portable automatic tide gage" type described by Schureman (1941, pp. 18-25). The same type system was operated from October 1962 to October 1963 at the end of the Crystal Beach Pier located near Destin, Florida, and 81.5 kilometers west northwest of the St. Andrews Pier. As is

common among tide gage installations, it was difficult to keep open the orifice at the bottom of the stilling well due to marine fouling and to keep the float completely unrestrained within the well. After reduction and smoothing, water elevations should be correct to well within 0.1 meter and recorded time should be within ±5 minutes. Relative values over a few tidal cycles should be two or three times more precise.

B. Shipboard Survey Data

The northeast Gulf surveys originally were designed to satisfy two main requirements. One was to provide "background" information on the physical environment over the continental boundary to aid in interpretation of phenomena observed in the immediate vicinity of the two nearshore platforms. The scope of the survey program generally was expanded to emphasize direct observation of mesoscale phenomena over the larger reaches of the boundary region shown in Figure I-1. Initial survey efforts were mainly exploratory being conducted as an adjunct to the localized observational program at the platforms. As personnel and equipment were added and techniques were improved, it became possible to improve spatial and temporal sampling distributions and to orient data collection towards the needs of individual investigations. Consequently, data pertinent to circulation that were collected in late 1965 and early 1966 are more complete and better suited to detailed analysis than earlier hydrographic and current observations dating back to 1963.

1. General approach to surveys. A set of "standard" station positions gradually was generated which provided the basis for survey planning whereby maximum long term repetition could be accomplished at fixed geographic locations. Appendix A is a tabulation of standard stations giving coordinates and nominal depths. Throughout the text, hydrographic sampling

locations will be identified according to the standard station nomenclature unless otherwise noted.

A main feature of the overall arrangement of stations is the set of straight courses (transects) that are laid out roughly normal to the trend of depth contours on the shelf (Figure I-1). Transects are identified in relation to a nearby coastal city or dominant geographic feature, viz., Mobile, De Soto Canyon, Destin, Panama City, Cape San Blas for transects shown from west to east in Figure I-1. The most frequently sampled transect was off Panama City which passes through the two platforms (I and II). It should be noted that selection of station positions along the transects was governed more by water depth than horizontal separation, e.g., stations G31, IX, VI, IV and XI all lie on the 200 fathom (365 meter) depth contour. All depths are appropriate to standard sounding velocity (1463 meters per second) so are different from true depths in direct proportion to the actual velocity of sound. For general conditions in the survey region, actual depths are about two per cent greater than the sounding depths.

Most of the hydrographic station data and current observations were made from the R/V DROGUE, a 63 foot converted air-sea rescue vessel with a cruising speed of 12 to 13 knots. The R/V ALAMINOS, a 185 foot converted freighter operated out of Galveston by Texas A&M University, participated in several multiple ship surveys as did the R/V GULF RESEARCHER, a 65 foot "T" boat operated by the Gulf Coast Research Laboratory at Ocean Springs, Mississippi. Beginning in July 1965 the R/V STAGE TIDE, a 43 foot aluminum launch with a cruising speed of 20 knots, was operated out of Panama City in addition to the DROGUE. All of these vessels were equipped with loran "A" receivers which, together with precision depth recorders or standard fathometers, furnished the main basis for navigation. A variety of checks on positioning indicated that a nominal accuracy of ±0.5 nautical miles (about one kilometer)

was realizable over most of the region from Cape San Blas to Pensacola. Accuracy of loran positions deteriorated westward in the survey region. A 36 foot personnel launch, the ANTILLA, was used for sampling in the nearshore region but was not equipped with loran and seldom ventured further offshore than station I.

2. Hydrographic observations. Temperature and salinity were selected for almost exclusive observational attention from among a broad range of potentially useful water mass properties. There were three primary reasons for such a delimitation: (1) main parameters for computation of density, (2) ease and reliability of acquisition and (3) simplification of survey procedure to enhance synopticity and limit personnel requirements, both at sea and ashore. In regard to synopticity, it is noteworthy that typical "on station" time for hydrographic data varied from less than five minutes nearshore to not more than 30 minutes at the offshore perimeter of the survey area. Minimum sampling time also was important in that the endurance of the R/V DROGUE was two to five days and its operation was susceptible to curtailment in the event of foul weather.

Prior to September 1965, hydrographic stations consisted of a bathythermograph (BT) cast together with water samples collected at selected depths for subsequent salinity analysis. "Surface" temperature observations and salinity samples were taken at a depth of about one meter below the water surface in an effort to minimize variability associated with diurnal and short term wind influenced transfer processes through the air-sea interface. Depths of water samples taken by Nansen bottles clamped on the BT wire were estimated on the basis of wire angle measured at the surface and maximum descent depth of the BT (as subsequently read from its temperature versus depth trace). These estimates probably are accurate to about five per cent.

Temperature and depth corrections were made for each BT slide trace before being photographed at Texas A&M. The temperature correction was based on an "average" deviation for selected periods of data during which the differences between thermometrically observed surface temperatures and the indications of an individual BT were reasonably constant. Slides were discarded if the differences between thermometer and instrument deviated by more than a few tenths of a degree from the "average" correction or if subjective analysis of data logs and thermometer readings did not give sufficient reason to discard individual bucket thermometer indications. Absolute accuracies of corrected BT traces probably are within 0.4°C and relative precision between traces from adjacent stations within 0.2°C.

Salinity (chlorinity) determinations of water samples normally were made at the Environmental Research Facility (ERF) in Panama City within a week or so after collection. Virtually all of the determinations were made by means of a Model 6210 inductive salinometer manufactured by Bissett-Berman Corporation (BBC). The standard $AgNO_3$ titration method was employed for the remaining samples and also used as a cross check against the inductive salinometer.

Intercomparisons were made several times each year between the salinity determinations made at the ERF and those made by titration or inductive salinometer at the Gulf Coast Research Laboratory and Texas A&M University. Samples for intercomparison were drawn from the same Nansen bottle and determinations made as soon thereafter and as simultaneously as practicable in an effort to avoid changes due to leakage, evaporation, crystal formation and biological alteration. The results of the most recent series conducted in 1965 are summarized by Gaul, Boykin and Letzring (1966, pp. 3-4). These indicate that the BBC salinometer used at the ERF yields values averaging from 0.006 to 0.008‰ less than the Australian

salinometer which is used as a primary standard by Texas A&M University. Standard deviations of the differences were in the range from 0.003 to 0.005‰.

In September 1965 a salinity/temperature/depth (STD) system was installed aboard the R/V DROGUE. The STD produces continuous profiles of temperature and salinity versus depth. A detailed discussion of the STD and its performance characteristics is given in Appendix B. The approach to reduction of the STD data is outlined in Chapter III.

The usual technique for final field calibration of the salinity part of the STD is adjustment of a device on the conductivity transducer until indicated salinity values read from the chart match those obtained from water samples collected more or less simultaneously with and at the approximate depths of the chart readings. Under conditions frequently encountered in the field this calibration procedure may be inadequate; indeed, where significant salinity microstructure is present, the STD should be capable of giving better results than can be obtained by water sampling. Salinity samples were taken frequently in conjunction with STD casts to furnish data for subsequent comparison and error correction where necessary. As shown by Gaul, Boykin and Letzring (1966), it was necessary to make a 0.17‰ correction to STD salinity values obtained prior to recalibration of the system in October 1965. For the remainder of 1965, average differences were found to be within 0.01‰ and no correction was applied. Corrections ranging to 0.06‰ were applied to data collected in 1966.

3. Current measurements. Three techniques are described below which were used for direct measurement of currents at locations other than the platforms. The majority of direct current observations were made in 1965 and 1966 with "parachute drogues" in the vicinity of various stations in the survey area. "Tethered drogues" and current meters (Savonius rotors and vanes) were employed during 1963-1965 for most of

the shipboard measurements made at stations J, R and VIII. The current meters and submerged buoy mooring system were essentially identical to the platform systems except that electrical cables were suspended from the water surface by small floats or laid along the bottom to the vessel which was anchored bow and stern in the immediate vicinity.

The tethered drogue system consisted of a weighted plywood cross suspended with a fine line from small floats, a measured neutrally buoyant (nylon) line between the floats and the vessel, a stop watch, compass and log sheet. The current cross was made of two rectangular vanes cut from marine plywood and carefully treated with epoxy resin and paint to minimize water absorption. The vanes were 0.6 meter wide and 0.45 meter high and were assembled in pairs to form a perpendicular cross. The buoyancy of the cross was made slightly negative by attaching about four kilograms of iron sash weights at the bottom. As many cylindrical plastic floats (usually three or four, each displacing about 0.01 cubic meter) were added at the surface end of a fine nylon line as required to keep the system afloat. The length of the connecting line determined the nominal depth to the cross (level of current observation). An individual observation of current speed was made by measuring the time required for the drogue to drift a prescribed distance (usually in the range of 10 to 50 meters) as ascertained by paying out the tether line from the anchored vessel. Direction was estimated by sighting the angle of the tether line relative to the longitudinal axis of the ship and also recording the ship's heading according to its compass. Speed and direction observations were made about hourly at each of three levels using separate drogues. Accuracies of the measurements are unknown but probably should be of the order of ±0.05 meter per second for speed and ±10 degrees for direction.

The parachute drogues were of the same type as described by Volkman, Knauss and Vine (1956). Parachutes were of the

personnel type used by the U.S. Air Force and had a nominal open diameter of 28 feet (8.5 meters). The chute shrouds were attached to and separated about 0.5 meter by a wooden bridle upon which was hung a ballast weight (usually chain) of about nine kilograms. A measured length of 3/64 inch (0.12 centimeter) diameter stranded wire rope connected the parachute assembly to a surface float that consisted of rectangular styrofoam blocks about 0.6 meter square which were stacked to give a total thickness between 0.2 and 0.3 meters. A vertical aluminum mast about 3.2 centimeters in diameter and 6 meters long passed through the styrofoam and was secured at its midpoint which also was the attachment point for the connecting cable. Two or three kilograms of ballast was secured to the bottom of the mast and a screen mesh radar reflector at the top. There was a nylon marker flag below the radar reflector together with a dry cell light assembly. The total mass of appurtenances on the mast above the water surface was about half a kilogram. Various techniques were employed to insure that the parachute would be constrained from opening until it had approached its maximum depth of descent.

Two methods were used for tracking parachute drogues. The simplest merely entailed taking a loran fix while the vessel was hove to in close proximity to the drogue. Normal positioning accuracies were those of the loran which, as previously discussed, were found to be within one kilometer over most of the survey area east of Pensacola. The second method required emplacement of a "reference" buoy having a surface float assembly similar to that of the drogues, a gravity anchor and a short scope mooring line (usually 1/8 inch diameter wire rope about ten per cent longer than the nominal water depth). The absolute accuracy of the reference buoy position depended on loran accuracy and lateral movement of the surface float permitted by anchor line scope. Repeated fixes on reference buoys indicated that the latter was well within accuracy limits

of loran fixes. Positions of drogues were determined by means of radar range and azimuth which were read at the same time as compass heading while the vessel was hove to in close proximity to the reference buoy. Maximum radar ranges normally were four to six miles under operable sea conditions and plots of successive positions indicate that azimuths were normally within ±5 degrees.

III. HYDROGRAPHY

A. General Approach to Analysis

There were three primary aims that governed the general approach to analyzing the hydrographic data: (1) assessment of temporal variability, (2) spatial characterization of the environment and (3) estimation of circulation features from hydrographic distributions. Temporal variability of the hydrography provides some clues as to corresponding changes in circulation but also is an important factor in evaluation of quasi-synoptic observations. Spatial distribution of density furnished the basis for deduction of the main circulation features in the absence of direct current measurements. The entire approach to this study is predicated on the assumption that a good correlation exists between hydrography and circulation.

A main concern in the data collection program has been with comparability of observations made at various positions in the survey area over a given time period. Obviously, the spectrum of local variability dictates time limits within which a survey may be considered "synoptic." Defant (1950) developed criteria for taking into account the influence of internal waves of tidal period but other phenomena can have a major impact on the degree to which a particular observation can be taken as representative of a given temporal span. Indeed, internal tides in the Gulf appear to be of minor importance relative to short term fluctuations in the quasi-steady circulation.

1. Basic relationships. Temperature, salinity and potential density are the only hydrographic variables considered in this study. Potential density is computed from observed values of temperature and salinity and is expressed in terms of sigma-t

(σ_t) according to the definition

$$\sigma_t = 1000(\rho_{st} - 1) \qquad \text{(III-1)}$$

where ρ_{st} is the density which the water would have at atmospheric pressure. The usefulness of sigma-t derives from its being a nearly conservative property. Another convenient derived quantity is δ_{st} which is directly related to sigma-t by

$$(\alpha_{35,0,0} + \delta_{st})(1 + \sigma_t) = 1 \qquad \text{(III-2)}$$

where $\alpha_{35,0,0}$ = 0.972643 milliliters per gram and is the reciprocal of the density of seawater at atmospheric pressure having a salinity of 35‰ and a temperature of zero degrees centigrade. Following the suggestion of Montgomery and Wooster (1954), the quantity δ_{st} will be called "thermosteric anomaly" and isopleths of thermosteric anomaly or sigma-t will be called "isanosteres." Relationships between temperature, salinity, pressure, specific volume, sigma-t and the various anomalies are widely reported (for example, see Sverdrup, Johnson and Fleming, 1946).

2. Data reduction. Reduction of bathythermograph data and determination of salinities are described in Chapter II. The approach to reducing STD traces deserved special mention in that these continuous profiles have proven so much superior to BT and water sample data that most of the hydrographic analysis is restricted to the eight months during which the STD was in use.

A sample set of STD traces for four stations on the Panama City transect are shown in Figure III-1. Some features are worthy of particular attention. The temperature traces characteristically exhibit abrupt changes in vertical gradients. Sharpest gradients and greatest excursions occur at the top of the seasonal thermocline but abrupt changes are common all the way to the level of the salinity minimum. The step-like thermal structure at considerable depths has been noted by Lee and

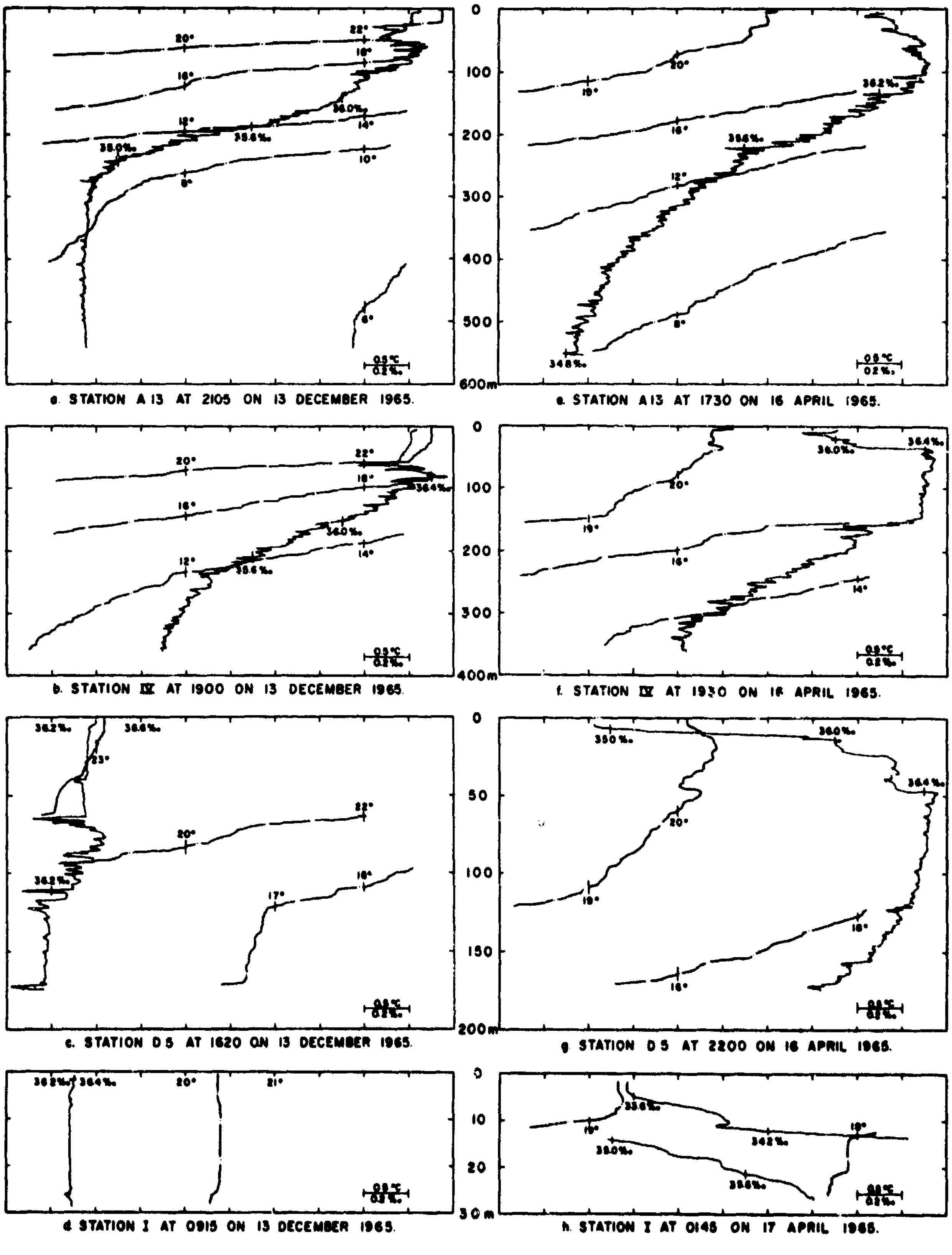


FIGURE III-1. Sample STD traces taken off Panama City in December 1965 and April 1966.

Cox (1966) from observations made in the Pacific Ocean by completely different techniques. The dynamical aspects of this phenomenon will not be considered but its existence will be seen to have considerable impact on techniques for analyzing STD data.

Except for shallow water stations such as I and II, all salinity traces are characterized by a much higher degree of irregularity than is evident in the temperature traces. This feature is explained qualitatively by the presence of the previously mentioned abrupt changes in temperature gradient which cause deviations in salinity indicated by the STD in accordance with the analysis presented in Appendix B. The temperature detection probe and probe for temperature compensation of conductivity have the same nominal time constant (about 0.35 seconds) so taking into account that usual descent rates were from 0.5 to 1.5 meters per second, the lower limit of detection for vertical spatial variations was less than one meter. Thus, it appears that variability of indicated salinity must be due either to actual salinity microstructure having vertical scales of the order of one meter or the influence of temperature gradient variability of the same scale on the conductivity sensor having a time constant of the order of one millisecond. The evidence gleaned from reduction of several hundred STD traces seems to overwhelmingly favor the latter as being almost solely responsible for irregularity of the salinity trace.

Several techniques were tried for reading values from the STD traces and applying Equation (14) of Appendix B. These were abandoned because reading at close enough intervals (in the neighborhood of one meter) to achieve reasonably accurate corrected salinities required an unacceptably large amount of time and effort. One such technique was used for data read at "standard" depths for the purpose of making a general summary of hydrographic data collected in the northeast

Gulf (Gaul, Boykin and Letzring, 1966).

The method finally used for reducing the STD data took advantage of the characteristic "steps" in the temperature traces indicating the presence of sharp thermal stratification, i.e., isothermal or nearly isothermal layers separated by regions of sharp gradient. Scales of these strata typically are of the order of meters which are sufficient for the compensation probe of the descending transducer to equilibrate while in the relatively uniform temperature region. By giving particular weight to indicated isothermal regions extending over a few meters or more and requiring that the corrected salinity be continuous and well correlated with temperature, it was possible to smooth each salinity trace by hand. The somewhat subjectively drawn "corrected" trace was mainly an envelope enclosing the maximum excursions to the right (positive) side of the salinity trace because the usual situation was of monotonically non-increasing temperature. Positive temperature gradients do occur in which case the envelope was on the left (negative) side of the trace.

The "subjective" method outlined above immediately raises the question of reproducible accuracy. One index is obtainable from the calculation made at the end of Appendix B where a salinity error of about 0.3‰ was computed for the somewhat extreme conditions cited. Salinity deviations of up to one part per thousand have been encountered but only at the top of an extremely sharp seasonal thermocline. It is apparent from Figure III-1 that the range of salinity variations stays roughly within 0.1‰. Placing the envelope on the proper side of the trace as dictated by Equation (B-14) and taking cognizance of conspicuous instances of isothermal layers assures a final accuracy near 0.02‰ (the scale interval of the chart paper) except in extreme cases. This assertion is borne out by a comparison given in Table III-1 between salinities tabulated by Gaul, Boykin and Letzring (1966) that were computed

TABLE III-1. Comparison of salinities corrected using Equation (B-14) with values obtained from traces smoothed by hand for selected stations taken on 13 December 1965.

Station	Time (CST)	Depth (m)	Computed Salinity	Smoothed Salinity
A13	2105	1	36.34	36.32
		15	36.32	36.32
		30	36.26	36.25
		50	36.33	36.39
		75	36.32	36.35
		100	36.15	36.15
		150	35.94	35.94
		250	34.99	35.00
		350	34.86	34.86
		500	34.84	34.85
IV	1900	1	36.34	36.31
		15	36.31	36.31
		30	36.29	36.29
		50	36.29	36.26
		75	36.49	36.45
		100	36.28	36.30
		150	36.19	36.00
		250	35.42	35.42
		350	35.21	35.21
D5	1620	1	36.40	36.40
		15	36.36	36.36
		30	36.36	36.36
		50	36.34	36.35
		75	36.41	36.44
		100	36.32	36.36
		150	36.17	36.18
		175	36.17	36.18

using Equation (B-14) and those read from the "corrected" trace drawn by hand for the casts of Figure III-1. In at least one instance of large deviation (values for 150 meters at IV) it is probable that the difference is attributable to selection of indicated values for correction by Equation (B-14).

The levels for reading temperatures and salinities were selected subjectively at "breakpoints." The number and depths of breakpoints depended on the shape of the curve. Breakpoints were selected at depths where the temperature gradient significantly changed. Generally there were in excess of 20 breakpoints used for casts of 500 meters or more. This would be comparable to having data from at least the same number of Nansen bottles whose depths had been preselected so as to give the best possible representation of the typically irregular temperature and salinity profiles; perhaps double the number would be needed for equivalent representation under actual operating conditions.

3. Selection and presentation of data. Hydrographic and current surveys were conducted over the northeast Gulf from May 1963 to June 1966. The hydrographic data have been summarized in a series of reports (Gaul and Boykin, 1964 and 1965; Gaul, Boykin and Letzring, 1966). Prior to September 1965 the hydrographic observations consisted mainly of BT casts accompanied by a limited number of water samples. A summary of such observations made along the Panama City transect is given in Appendix C. After the STD system went into service about the middle of September, BT's and water samples were taken only for purposes of verification or obtaining supplementary data as in the case of multiple ship surveys. A summary of STD casts made along the Panama City transect is given in Table III-2.

The Panama City transect was selected for analysis of temporal variability and for comparison of the hydrographic

TABLE III-2. Summary of STD observations along transect off Panama City.

Starting Time and Date	Elapsed Time	Terminal Stas. Shallow	Deep	No. of Stas.
1218/07SEP65	7.2 hrs.	II	IV	12
0950/13SEP65	14.0 hrs.	II	IV	10
1635/14SEP65	4.0 hrs.	II	D3	7
0230/18SEP65	4.2 hrs.	II	D3	7
0905/20SEP65	3.7 hrs.	II	D2	7
0600/23SEP65	3.2 hrs.	II	D3A	6
0800/05OCT65	5.5 hrs.	M4	D4	8
0605/13OCT65	17.5 hrs.	II	A33	16
1240/25OCT65	8.2 hrs.	II	IV	10
2105/15NOV65	6.5 hrs.	II	IV	10
1455/18NOV65	16.7 hrs.	II	A13	28
1345/19NOV65	7.5 hrs.	II	IV	14
0755/12DEC65	13.0 hrs.	II	A13	16
1025/18DEC65	4.2 hrs.	II	D3	8
1120/14FEB66	8.2 hrs.	I	IV	12
0910/15FEB66	3.2 hrs.	I	IV	10
1305/21MAR66	9.0 hrs.	II	IV	14
0845/25MAR66	14.0 hrs.	II	A15	19
0005/27MAR66	13.2 hrs.	I	A15	15
0830/14APR66	9.2 hrs.	II	A13	16
1730/16APR66	9.0 hrs.	II	A13	14
2200/24APR66	16.5 hrs.	I	A13	20
0925/29APR66	8.5 hrs.	I	D5	9
1715/30APR66	4.5 hrs.	I	D5	9

variables. Analysis of spatial distributions incorporates data from other transects and stations sampled within survey periods of a few days. The selection of specific surveys was guided by a variety of factors including areal coverage, types

and distributions of sampling, combination of hydrographic and current observations, regularity of patterns derived from analysis of the observations and the degree to which results seemed to be representative of the season during which the survey was made. Increased emphasis has been placed on the surveys during which the STD was in use.

Two main techniques are employed for r esentation of hydrographic data. Spatial distributions are illustrated by means of contoured fields of specified variables along vertical sections. Most of the sections are transects across the boundary at the locations shown in Figure III-1. Temperature-salinity (T-S) curves are used for water mass identification. This is a classical technique that is widely described (for example, see Defant, 1961, pp. 202-218) and normally used for characterizing large water masses below the seasonal thermocline and for analysis of mixing. The resolution of the STD system combined with the degree of synopticity achieved in the surveys has made possible water mass characterization over horizontal distances of the order of 10 kilometers. The T-S curves were plotted directly from values read at the breakpoints as described previously.

B. Comparability of Hydrographic Variables

In view of the large number of surveys limited to BT and water sampling and completed prior to September 1965, it is of interest to evaluate the comparability of temperature, salinity and density distributions. Examples chosen are from the Panama City transect as observed in December 1965 and April 1966.

Contours of temperature, salinity and sigma-t for December 1965 are shown in Figure III-2. The transect was run in the offshore direction from II to A13 beginning at 0810 and ending at 2105 on December 13th. The profiles for temperature and

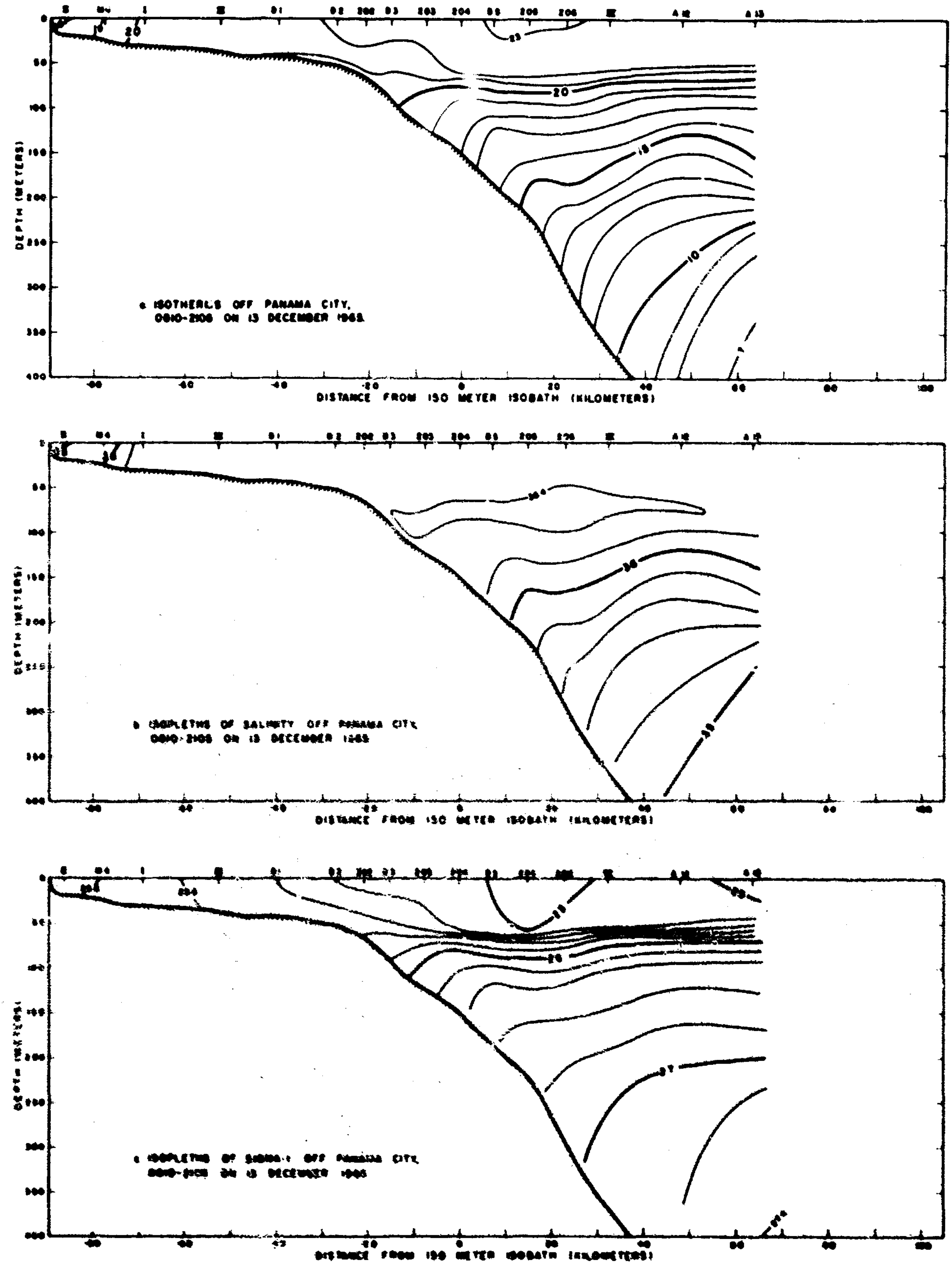


FIGURE III-2. Comparison of hydrographic variables along transect off Panama City, 13 December 1965.

salinity were contoured individually as was the isanostere section using sigma-t values computed from original temperatures and salinities. Sampling stations are shown along the top of each illustration. It is noteworthy that the temperature and salinity patterns are well correlated below the mixed layer with elevations of isopleths varying 50 meters or more in horizontal distances of 20 kilometers. The sigma-t isopleths are much smoother and more nearly horizontal. The variable current structure at about 150 meters in the vicinity of A12 that might be inferred from the isotherms is not indicated at all by the pattern of sigma-t.

Contours of temperature, salinity and sigma-t for April 1966 are shown in Figure III-3. Isopleths for this case were obtained by smoothing individually contoured profiles appropriate to two separate transects run successively. The first was run offshore covering the stations shown between 0830 and 1745 on the 14th. The second was run towards shore between 1730 on the 16th and 0235 on the 17th. Profiles for the separate runs revealed vertical differences approaching 20 meters and horizontal differences of several kilometers between given isopleths, especially over the shelf. Nevertheless, there could be little doubt as to the preservation of dominant features over the three day period since in <u>all</u> instances given isopleths intersected at one or more points along the profile. The 10 and 11 degree isotherms did not change significantly and neither did the 35.4‰ isohaline. An especially interesting feature is a water mass "transition" region in the vicinity of D2 to D3 indicated by abrupt changes in slope of the isotherms (dipping downward offshore) and the isohaline (dipping downward onshore). Since these changes in slope are not apparent in the isanosteres (Figure III-3c), it can be concluded that mixing occurs in such a way as to maintain vertical stability. The occurrence of this region at the break in bathymetric slope is not considered to be coincidental.

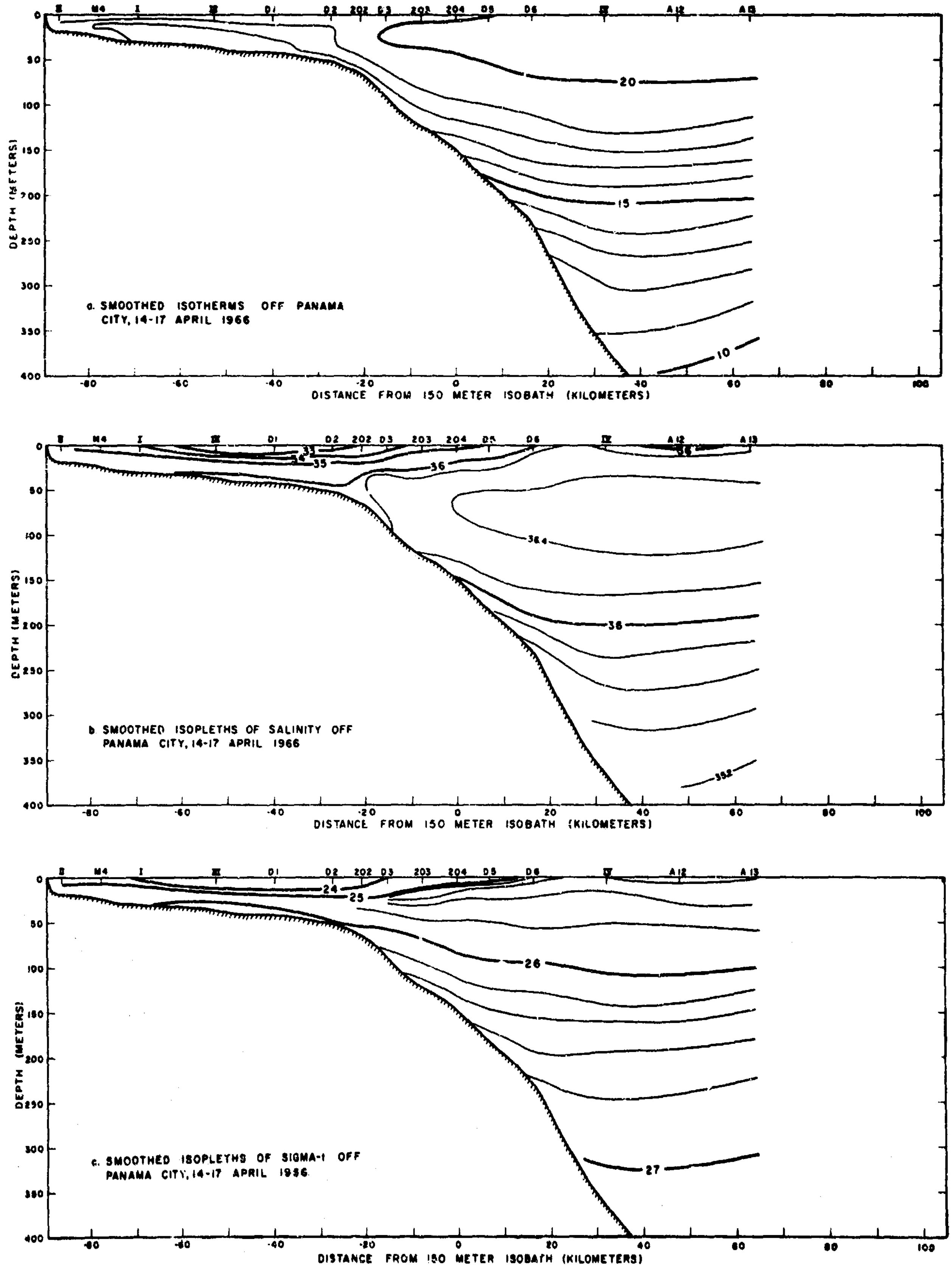


FIGURE III-3. Comparison of hydrographic variables along transect off Panama City, 14-17 April 1966.

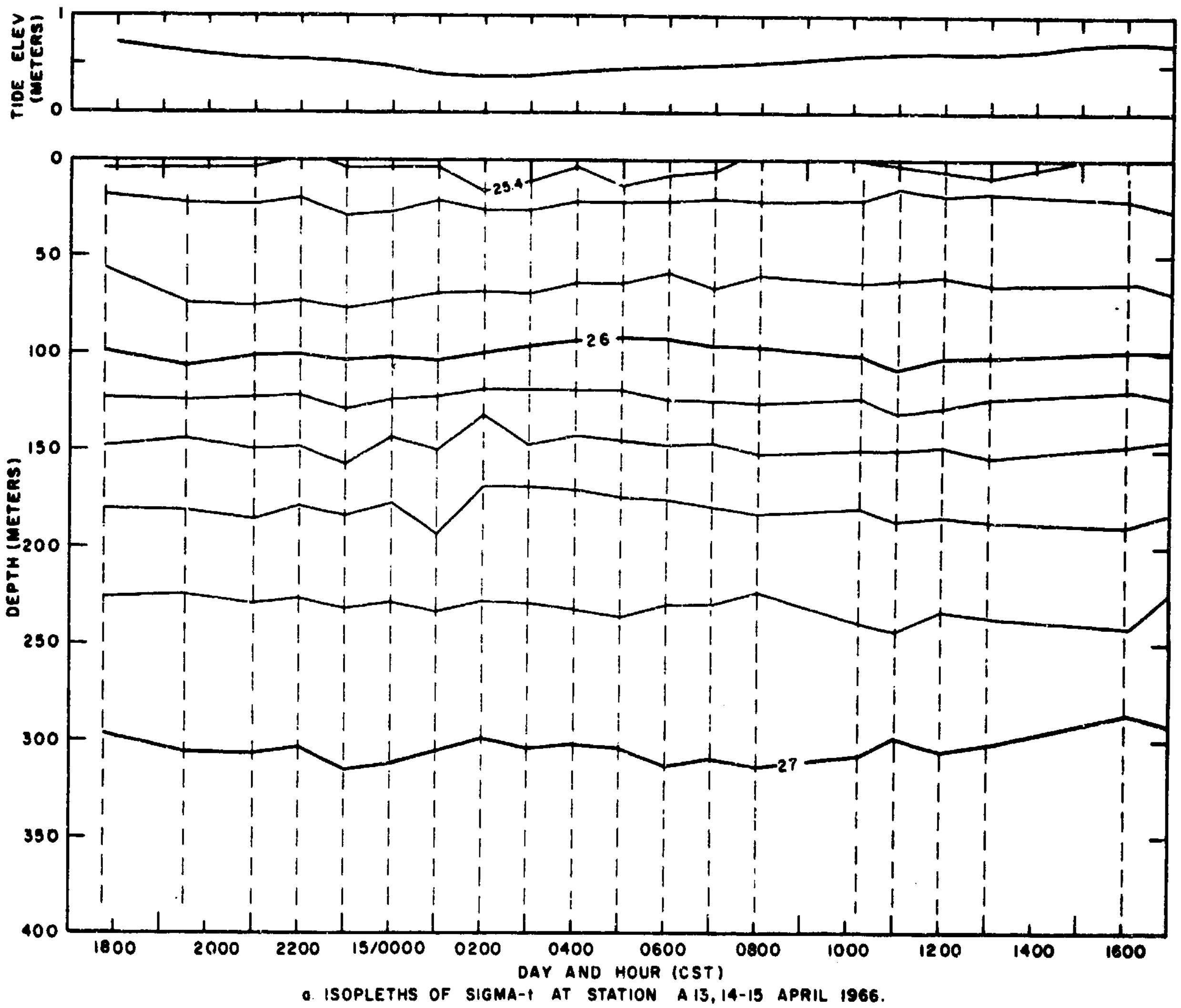
C. Temporal Variability

Local variations are of major importance in any interpretation of survey data. Considerable emphasis was placed on scheduling surveys and arranging the sequence of stations such that estimates could be made of local variability over a temporal range from hours to seasons. Attention was concentrated on the transect off Panama City.

1. Short term variation. For the purposes of the following discussion, short term variations will be taken as those having periods (in the discrete or spectral sense) shorter than a few weeks. The definition is not intended to be exact but rather to connote time spans shorter than can be associated with the natural seasons.

There is a significant store of temperature, salinity and current data, especially from Stage I, that attests to the presence of horizontal and vertical velocity fluctuations having periods of a few minutes or less. These are beyond the scope of this study except to note that they can be of sufficient magnitude to introduce significant errors in estimates of longer period motions. Spatial discontinuities and small scale variations (centimeters to fractions of a kilometer) often have been observed and pose a similar problem of "noise" superimposed on phenomena of interest.

Variations occurring over a few hours are of interest because six to ten hours typically were required to run a single transect (see Appendix C). Consecutive repetitions of the Panama City transect beyond the break in bottom slope seemed to reveal wave-like internal perturbations having vertical ranges exceeding ten meters and horizontal wave lengths of 20 to 40 kilometers. These suggested the possibility of internal standing waves so time series of one or two days in length were made at several stations, e.g., D5, IV and A13. Typical examples of results obtained are shown in Figure III-4



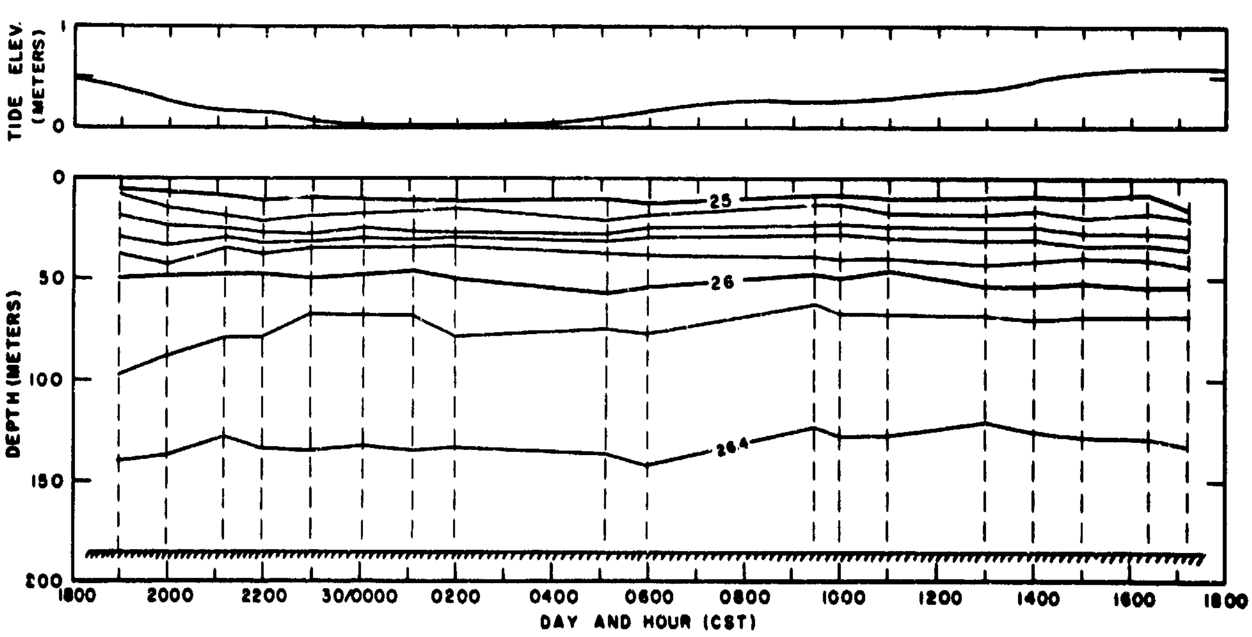


FIGURE III-4. Isanosteric time series at stations A13 and D5 in April 1966.

where the vertical dashed lines show the time of sampling. It is readily observed that a strong tidal period is not present and that isanosteres at various depths do not have an apparent phase relationship. Furthermore, maximum hour-to-hour changes generally are within a factor of two of the full range of vertical variation during the 24 hour observation period. These results stand in marked contrast to those of Salsman (1962) and Boston (1964) that revealed internal tides having ranges up to half the water depth in the very nearshore region at station II.

Time series were not taken of sufficient length to quantitatively evaluate variability over several days or a few weeks. Stations frequently were repeated during surveys lasting several days. Sometimes repeated values were consistent and as often variations were so large as to make questionable the validity of treating the survey data as quasi-synoptic.

2. Seasonal variation. Some notion of the seasonal fluctuation of the stratified water over the boundary can be developed from sigma-t sections off Panama City. In Figure III-5 are shown selected isanosteric profiles for August, October and December 1965. February, March and April 1966 are represented in Figure III-6. These profiles cannot be taken as representative of given months or of transverse slopes of isopycnic surfaces. Instead they tend to emphasize the very significant changes in density distribution, particularly below the seasonal pycnocline. Nevertheless, seasonal changes in the vertical density structure are clearly evident ranging from the summer situation of low density, well stratified upper layers to the relatively homogeneous higher density winter situation. Well stratified waters are typical over the entire shelf from April through September. Winter stratification in the nearshore region depends mainly on salinity since the water tends to be isothermal beyond station I.

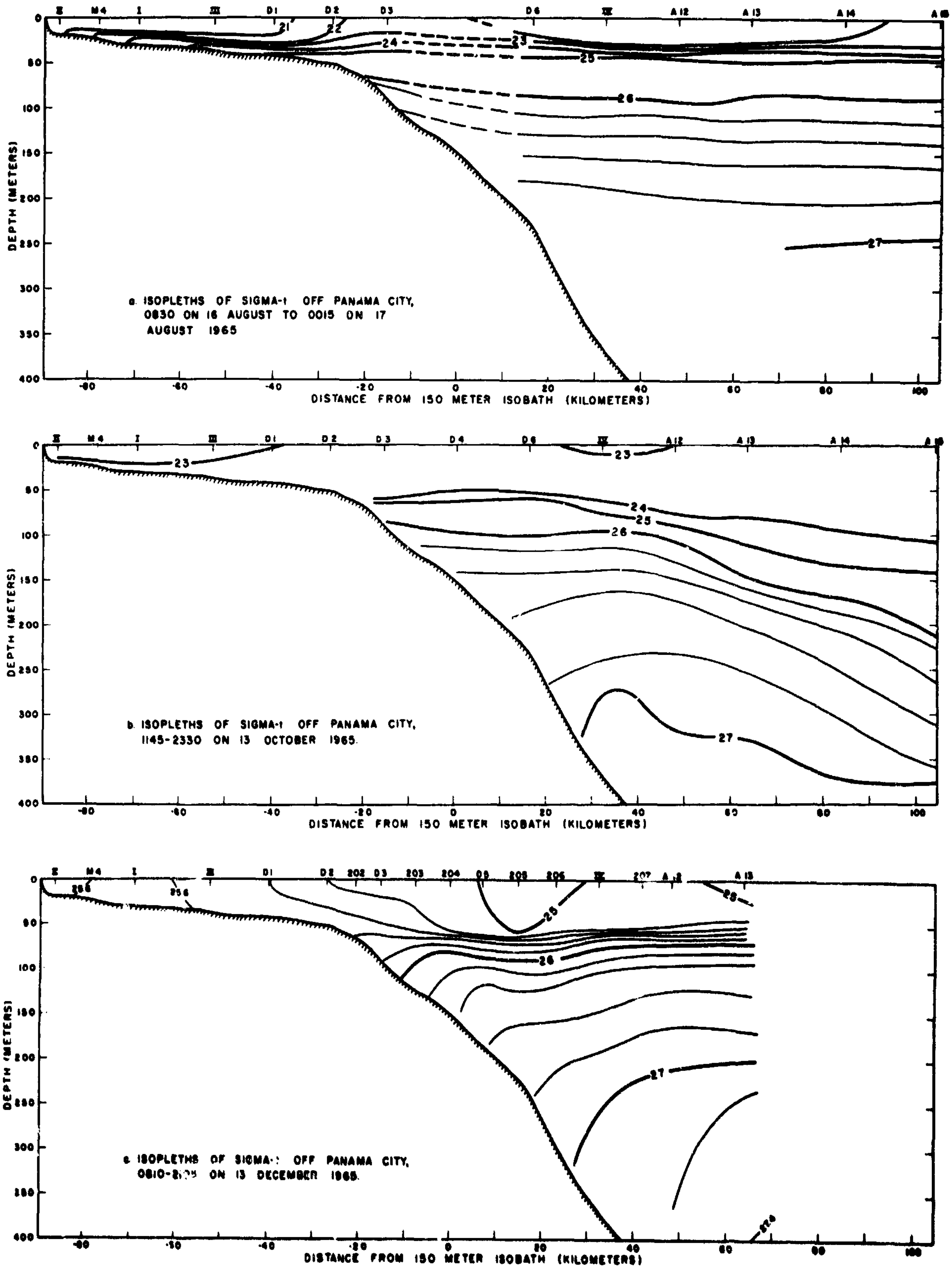


FIGURE III-5. Isancsteres along transect off Panama City in August, October and December 1965.

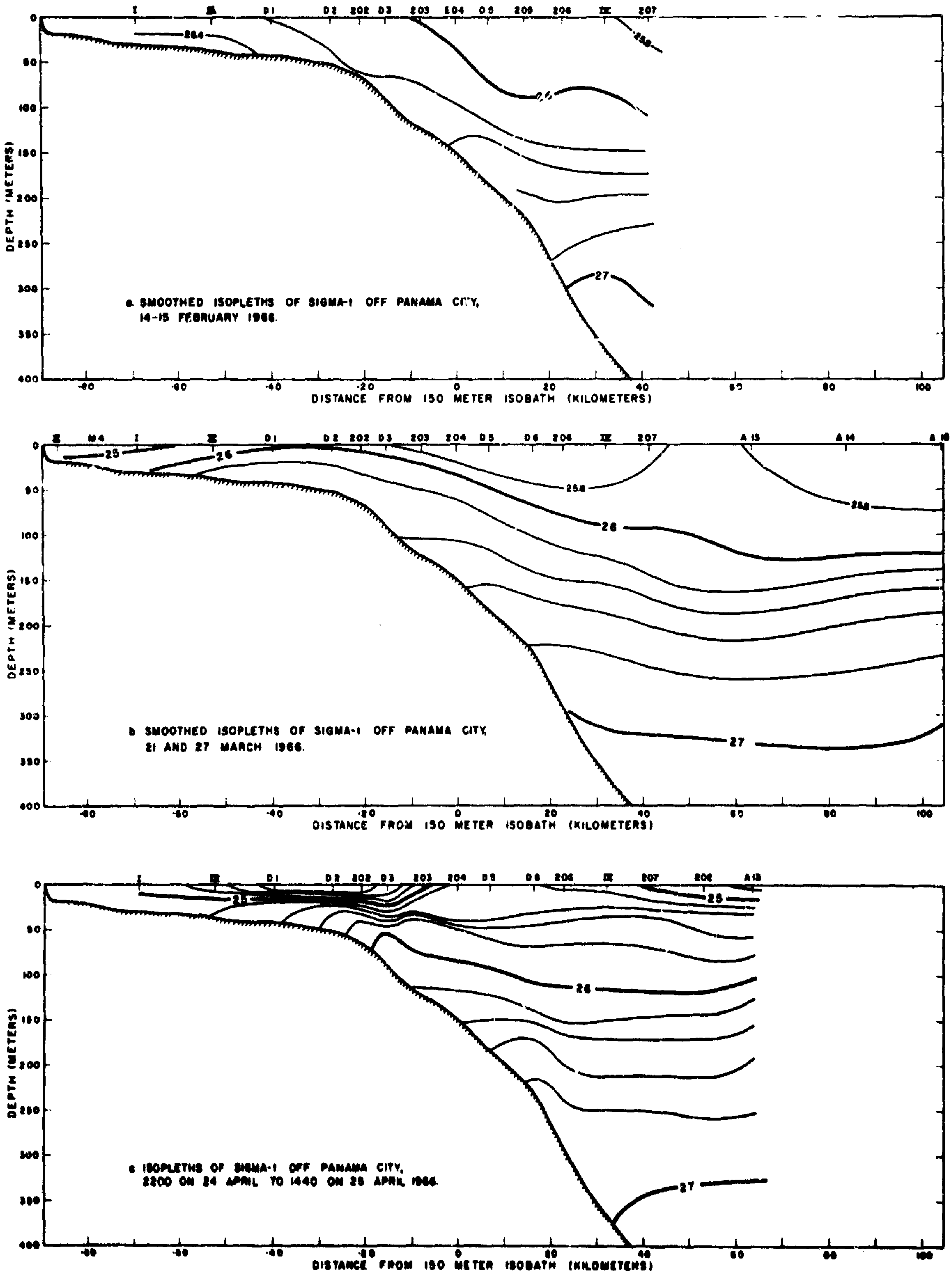


FIGURE III-6. Isanosteres along transect off Panama City in February, March and April 1966.

Another indication of seasonal variability is given by temperatures and salinities observed at station I in 1965. Averages of values grouped by months are given in Table III-3. Observations near the bottom were used to improve consistency and reveal the intrusion over the shelf of water from off-shore. No more than one pair of values was selected from observations made on a given day in an attempt to make the data more representative. Although the data are meager, the seasonal cycle is evident in both temperature and salinity. Extremes associated with winter appear to be in February and with summer in August.

TABLE III-3. Means and ranges by months of temperatures and salinities observed one meter above the bottom at station I in 1965.

Period of Observations	Temperatures (°C) Min.	Mean	Max.	Salinities (‰) Min.	Mean	Max.	No. of Obs.
5-13 Jan.	17.1	17.3	17.6	35.02	35.14	35.22	3
19 Feb.	----	15.6	----	---	35.35	---	1
3-31 Mar.	14.6	14.7	15.5	34.99	35.37	35.57	5
2-9 Apr.	14.6	15.5	15.9	35.52	35.58	35.66	5
10-21 May	18.4	19.3	20.3	34.98	35.13	35.23	4
1-26 June	21.1	24.2	26.6	34.90	35.21	35.65	8
20-22 July	24.5	24.7	25.1	35.43	35.65	35.79	3
16-25 Aug.	25.6	26.2	26.6	35.57	35.73	36.00	3
14-23 Sept.	26.4	26.5	26.6	34.71	35.08	35.32	4
5-25 Oct.	22.5	25.0	26.5	34.66	35.36	36.14	4
2-19 Nov.	21.9	22.4	23.6	35.26	35.50	36.02	4
13-18 Dec.	19.4	19.8	20.2	36.05	36.17	36.29	3

In Figure III-7 are shown T-S curves for selected STD casts taken at IV in the months specified. The curves are surprisingly consistent below the thermocline considering the character of profiles illustrated in Figures III-5 and

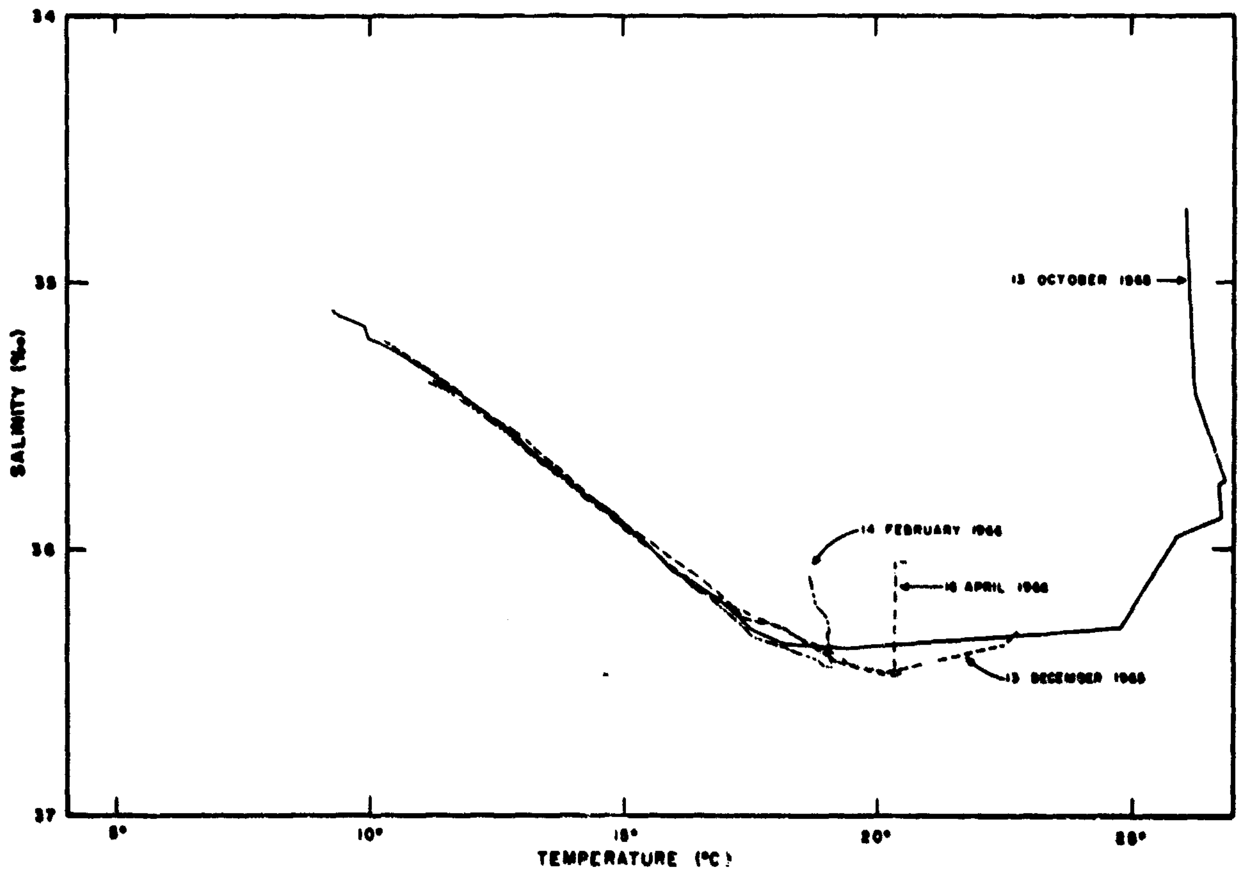


FIGURE III-7. Comparison of T-S curves for station IV during October 1965 to April 1966.

III-6. This seems to indicate that although the small scale circulation may have been quite variable (as suggested by Figures III-5 and III-6), there either was little net exchange by advection or mixing to alter the local water mass or the water mass was of great horizontal extent.

3. Annual variation. Only a hint of possible year-to-year variations may be gleaned from the data available because of its paucity and poor distribution. Temperatures and salinities observed above the bottom at station I and averaged by month are given in Table III-4. The number of observations contributing to each average are comparable to those of Table III-3 for each of the months represented. It is difficult to discern annual trends but it seems clear that for a given month there can be significant annual variations in temperature and salinity, i.e., more than two degrees and one part per thousand, respectively.

TABLE III-4. Comparison of averages by months of temperatures and salinities observed one meter above the bottom at station I during 1964-1966.

	Temperatures (°C)			Salinities (‰)		
Month	1964	1965	1966	1964	1965	1966
Jan.	----	17.3	17.2	----	35.1	36.0
Feb.	----	----	16.2	----	----	36.0
Mar.	----	14.7	16.9	----	35.4	35.6
Apr.	17.4	15.5	18.9	34.9	35.6	35.7
May	20.5	19.3	----	35.2	35.1	----
June	22.9	24.2	----	35.1	35.2	----
July	23.8	24.7	----	35.0	35.7	----
Aug.	24.3	26.2	----	35.7	35.7	----
Sept.	23.1	26.5	----	36.0	35.1	----
Oct.	23.4	25.0	----	35.6	35.4	----
Nov.	21.6	22.4	----	35.7	35.5	----
Dec.	17.7	19.8	----	35.3	36.2	----

Perhaps a better indicator of annual changes are the T-S curves for station IV shown in Figure III-8. In contrast to the relative comparability of T-S curves from October 1965 to April 1966 (Figure III-7), there is a several-fold increase in the spread between curves for a given month in three successive years (Figure III-8a). Of course there is some question as to the representativeness of the specific curves selected and this matter cannot be resolved for 1964 and 1965 since there are no other data available for station IV. The 1966 curves, however, were selected from a number of casts all of which fell within a range narrower than that of Figure III-7. It should be noted that for 1964 and 1965 straight line segments connect points at which temperature and salinity values were available.

D. Spatial Distributions

Quasi-synoptic spatial distributions of density form the foundation for interpreting the direct current measurements made in the northeast Gulf and for generalization of the quasi-steady circulation. The presentation below is restricted to instances where the local variations during the course of sampling are thought to be small compared to the field variations. In the previous description of survey procedures are given some of the techniques used to evaluate synopticity in relation to spatial scale.

1. Stratification. As can be noted readily from previous illustrations, e.g., Figures III-5 and III-6, the water is always stably stratified outside the break in bottom slope between D2 and D3. The typical winter condition is an essentially isopycnal water mass covering the entire shelf and extending below 50 meters offshore beyond station IV. Stratification below 200 or 300 meters does not exhibit any marked seasonal associations based on data now available. Significant

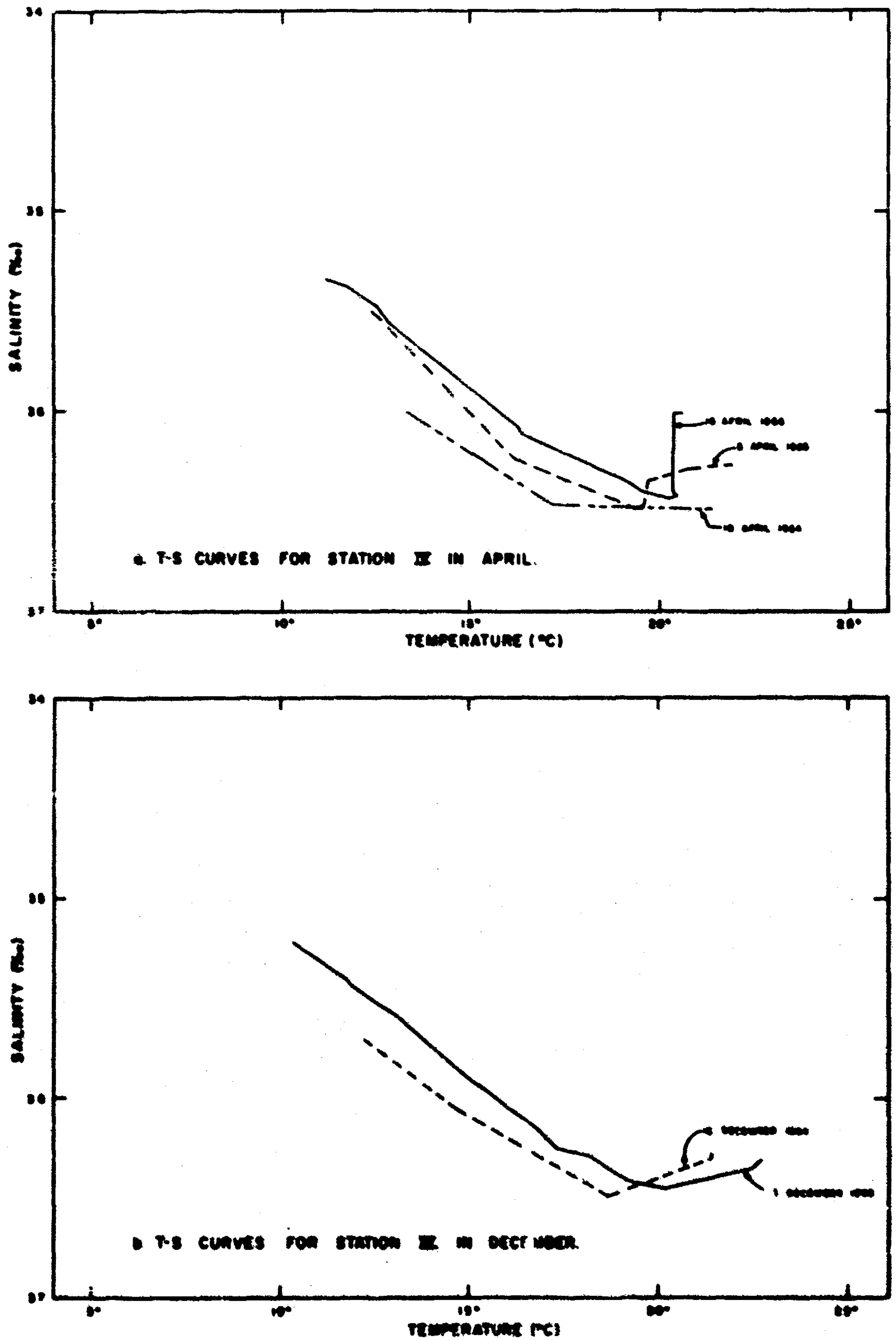


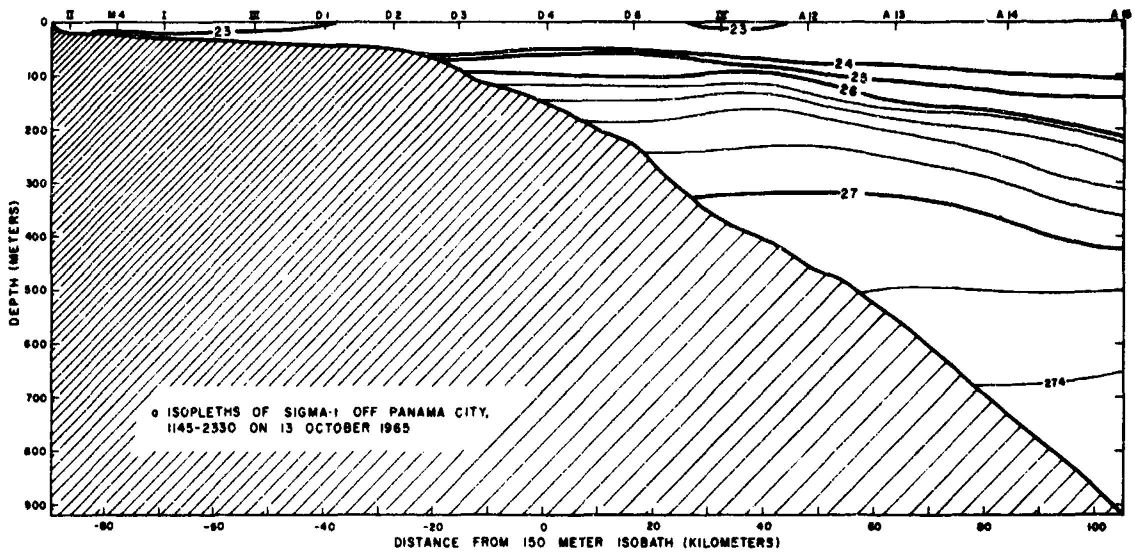
FIGURE III-8. **Comparison of T-S curves for station IV in April and December of 1964-1966.**

vertical density gradients begin to appear over the shelf in March and from May to September are extremely sharp as far inshore as the littoral zone. This sharp stratification will be seen to have a profound influence on circulation over the shelf.

2. Transverse density distribution. One conspicuous feature of the isanosteric profiles such as shown in Figures III-5 and III-6 are the sharp changes in slope as isopleths approach the boundary. The isanosteres typically slope downward towards shore although the opposite case occurs but seldom are slopes as steep at the intersection with the bottom. The downturn along the boundary is particularly conspicuous over the shelf when the water is well stratified. This suggests the normal existence of a frictional boundary layer 20 to 40 meters thick with a net transport onshore.

3. Horizontal density distributions along the boundary. Figures III-9 and III-10 were selected to illustrate horizontal density distributions over the shelf from De Soto Canyon southeastward to off Cape San Blas (Figure I-1). Figure III-9 is notable in that the section off Cape San Blas extends beyond the break in continental slope about 145 kilometer beyond the 150 meter isobath. The general trend of isanosteres is downward away from shore and also toward the southeast if comparisons are made along the isobaths. A strong influence of bathymetry on the transverse density distribution is evident from the abrupt change in isanostere slopes about 140 kilometers beyond the 150 meter isobath off Cape San Blas.

Although the transects in Figure III-10 do not extend as far offshore, significant differences from those of Figure III-9 for a month earlier are apparent. The isanosteres do not tend to deepen offshore; if anything, the reverse is true. The form of the isanosteric patterns off Panama City and Cape San Blas differ more significantly in Figure III-10 than in III-9. The isanosteres again tend to deepen toward the Cape



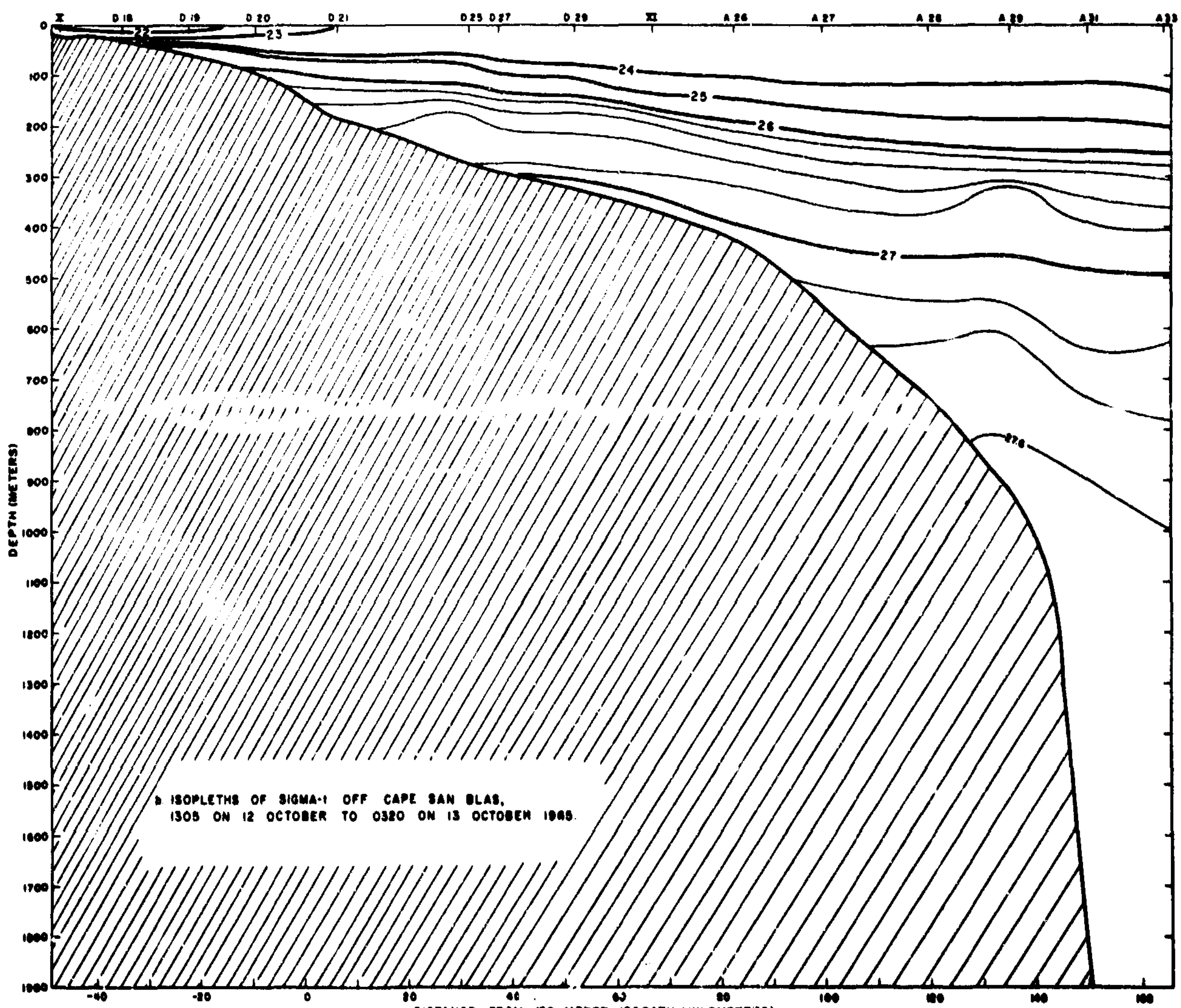


FIGURE III-9. Isanosteres along transects off Panama City and Cape San Blas, 12-13 October 1965.

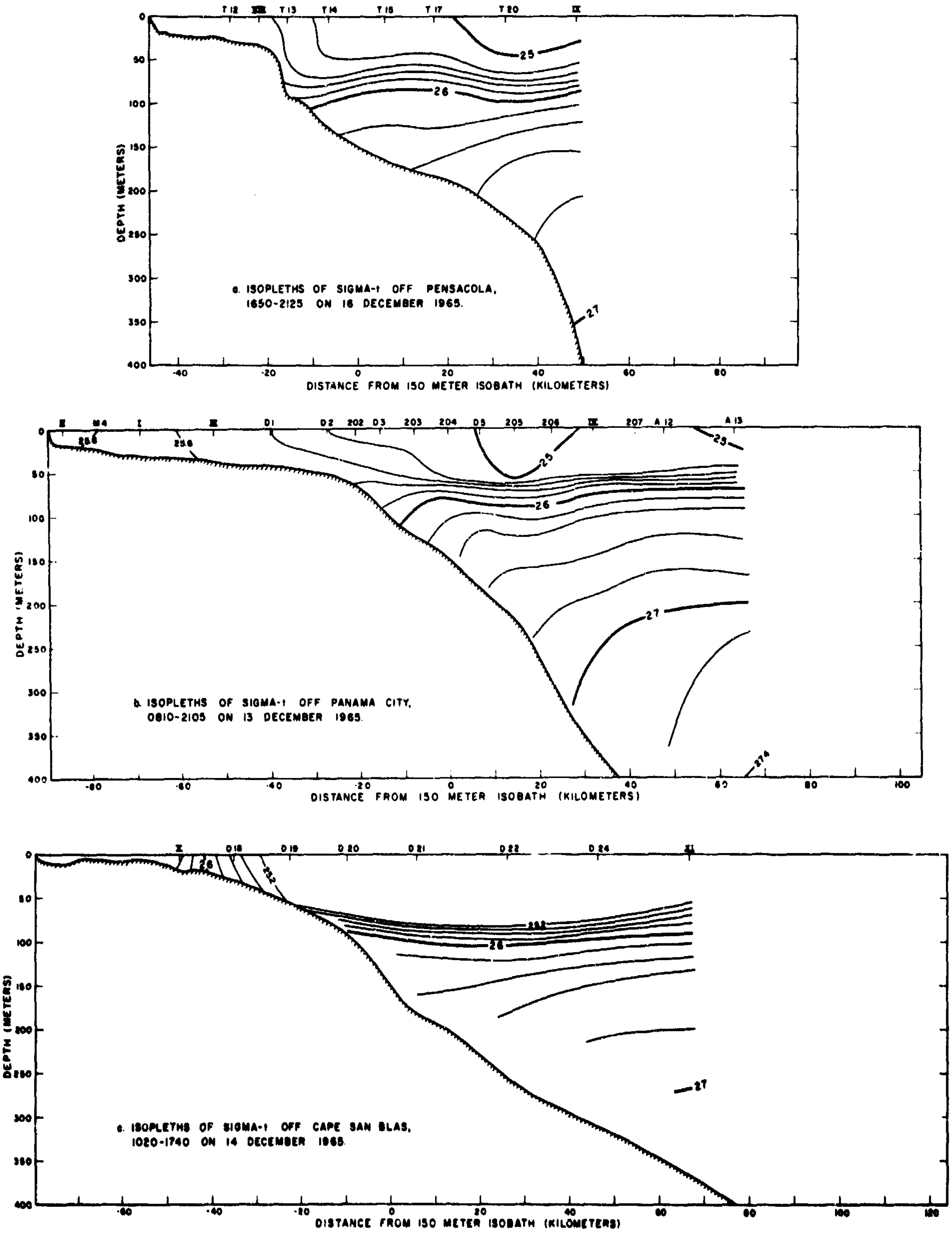


FIGURE III-10. Isanosteres along transects off Pensacola, Panama City and Cape San Blas in December 1965.

San Blas transect (southeastward). There appears to be a clear cut association of isanosteric profiles and bathymetry, especially along the De Soto Canyon transect.

Figures III-11 and III-12 give another view of horizontal distribution. The position of these sections may be ascertained from the stations noted along the top of each illustration which are located on Figure I-1. The section run in October (Figure III-11) cuts across De Soto Canyon westward from station IV and runs obliquely along the continental boundary to the submarine canyon south of Grand Isle, Louisiana. The section run in November follows almost the same westward course from IV to A6 but then runs in a direction more nearly parallel to the isobaths to M99 which is south of the delta and offshore from the submarine canyon. The isanosteres are more nearly horizontal along the boundary (west of A6) than across De Soto Canyon (A6 to IV). The conspicuous hump in the isanosteres at all levels in the sections across De Soto Canyon had suffered a westward displacement from an insignificant amount below 500 meters to 60 kilometers above 300 meters. Apart from the obvious implication that such a feature must have on circulation, it must be noted that there is no way of estimating its temporal continuity. The significant changes in the isanosteric patterns in less than a month emphasize the supposition that major changes in the quasi-steady circulation over the entire area of Figure I-1 can and do occur within periods of a few weeks.

In Figure III-13 are shown T-S curves for stations along the November section shown in III-12. Clearly evident are marked changes in water mass characteristics across the section. It is of particular interest that maximum salinities are at stations A1, A2 and A4 whereas M99, A6 and A11 are much closer to the characteristics of IV. This observation coupled with the isanosteric section suggest that water from offshore

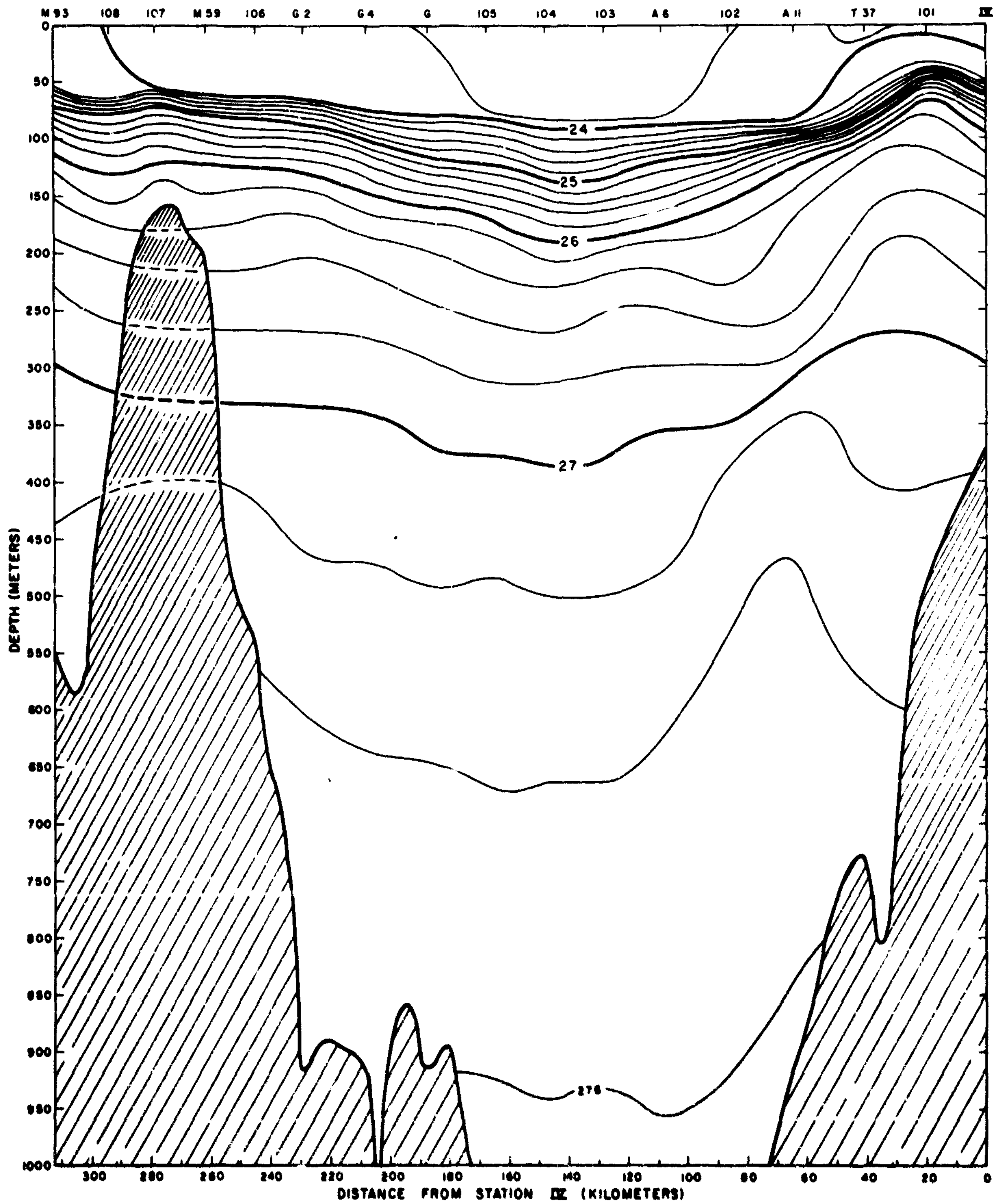


FIGURE III-11. Isanosteric section along continental slope from off Mississippi delta to off Panama City, 25-27 October 1965.

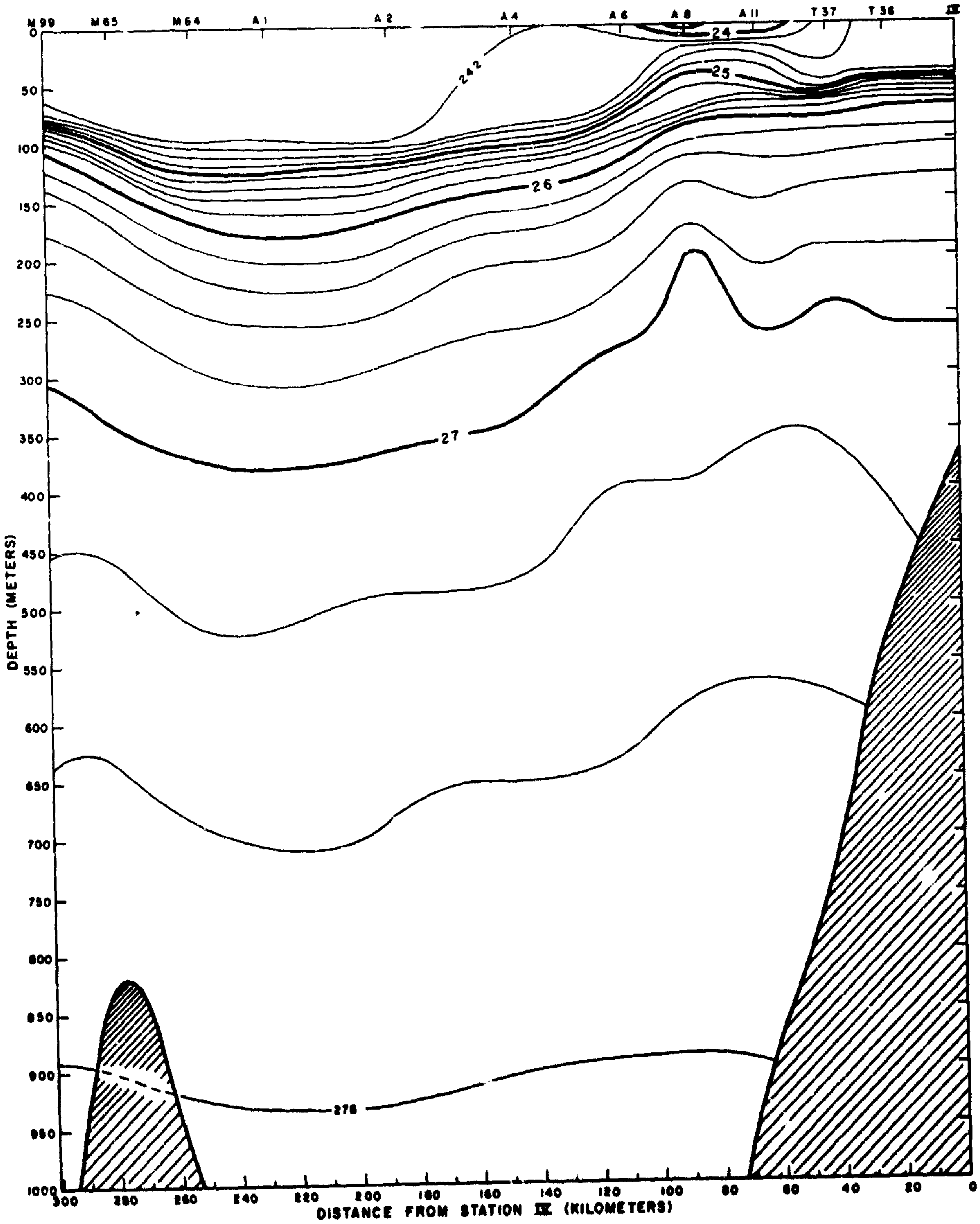


FIGURE III-12. Isanosteric section along continental slope from off Mississippi delta to off Panama City, 15 November 1965.

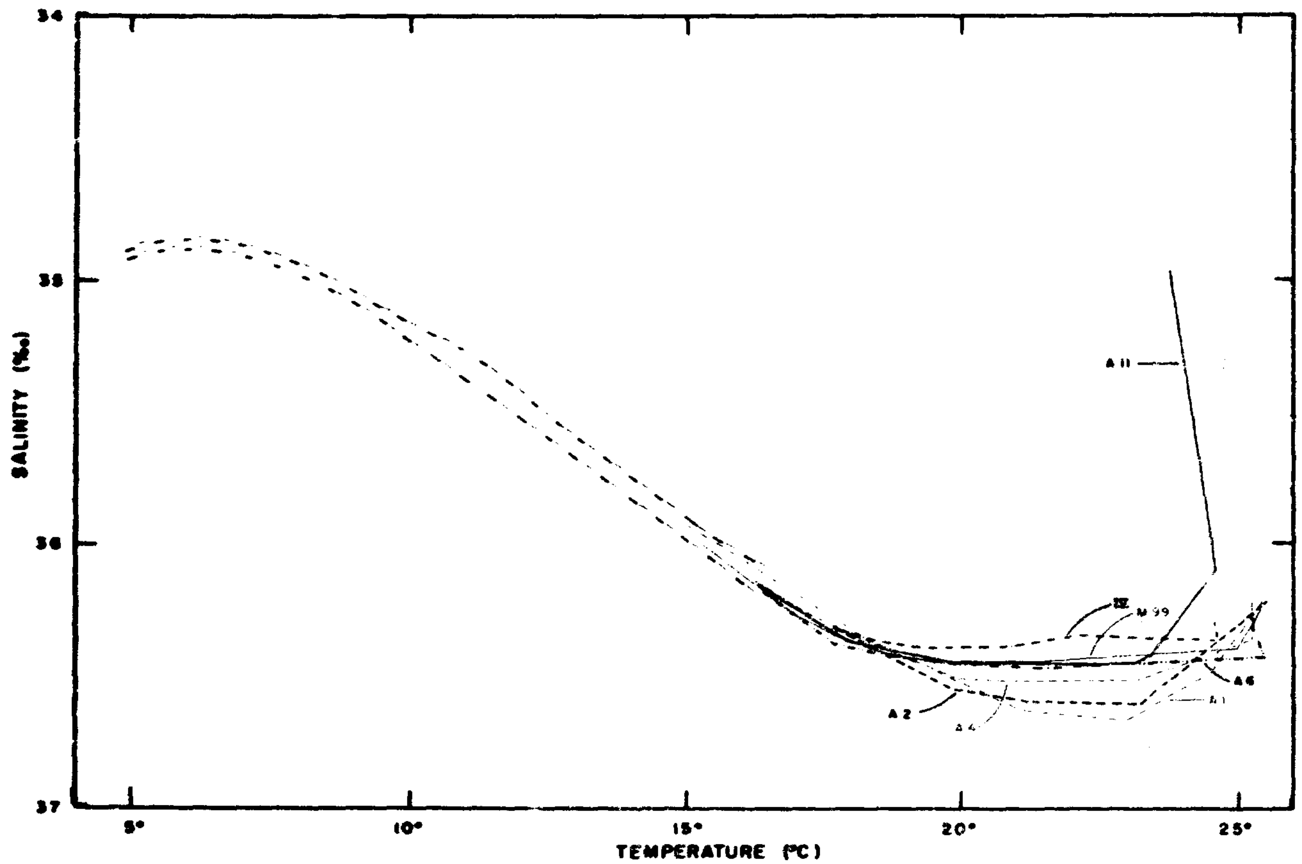


FIGURE III-13. Comparison of T-S curves for stations on section from off Mississippi delta to off Panama City, 15 November 1965.

was moving eastward obliquely onshore east of M99 and obliquely offshore west of A6. Such motion is not inconsistent with the existence of a cyclonic eddy about 60 kilometers across and centered between A8 and A11. The T-S curves indicate that most of the lateral mixing with nearshore waters that is associated with the circulation is taking place above the 26.3 isanostere (which corresponds to nominal values of 18 degrees and 36.35‰ for temperature and salinity, respectively).

IV. CURRENTS

A. General Approach to Analysis

Most of the direct current measurements were made in an effort to verify features indicated by hydrographic results or to investigate a specific phenomenon such as the internal tide. The number of current observations are limited because of logistical limitations and the choice in favor of hydrography to enhance synoptic areal coverage.

One of the main objectives of direct current observations was to "calibrate" circulatory inferences gained from the hydrography. This is particularly important in the boundary region where significant departures from geostrophy may result from frictional influence of the boundary. Another purpose was to establish relative magnitudes of tidal and quasi-steady components and to evaluate the "noise" level associated with meso- and micro-scale turbulence. Direct measurements also furnish indications of horizontal velocity shear associated with stratification or bathymetric features.

The current measurements taken at the deeper platform (station I) were reduced to the same form as the drogue data by constructing vector displacement diagrams. This was done by estimating hourly mean current speed and direction and calculating the displacement that would have occurred under steady state conditions. Successive displacements were plotted and the curves smoothed to produce a simulated current trajectory.

Net drift vectors were obtained from trajectories. From the straight line segment obtained from a trajectory or a vector displacement diagram over a given time interval, the net drift direction and speed were estimated.

Only a part of available data are summarized below. Particular sets of observations generally were selected as

representative although in some instances availability of data or illustration of an individual phenomenon took precedence. A summary of all observations made from shipboard and part of those made at station I is given in Appendix D.

B. Currents of Tidal Period

The main source of long time series of multiple level current observations was the meter array at the deeper platform (station I). An example of continuous record plotted from five minute averages is given in Figure IV-1. This example was chosen because of the extremely regular clockwise diurnal rotation of the upper water layer as indicated by the transducers at 6 meters below the surface. This regular rotation and the small range of variation in current speed are characteristic of an inertial current combined with a small range diurnal tide which is typical of this region. However, the current one meter above the bottom exhibits none of the expected features and even tends to rotate contra solem. The current direction at mid-depth clearly lags the rotation at six meters and suffers distortions which probably are associated with vertical migration of the pycnocline. This is a striking example of the influence of stratification on circulation. Cases of this general nature were common but not necessarily dominant. Nevertheless, instances were rare of uniform currents throughout the water column.

The vector displacement diagrams of Figure IV-2 were chosen to illustrate the wide range of flow regimes encountered. Figure IV-2d corresponds to the example of IV-1. Diurnal rotation of the surface layer is evident in most cases superimposed on a quasi-steady current. The aforementioned lack of coherence between surface and bottom currents is conspicuous in all cases.

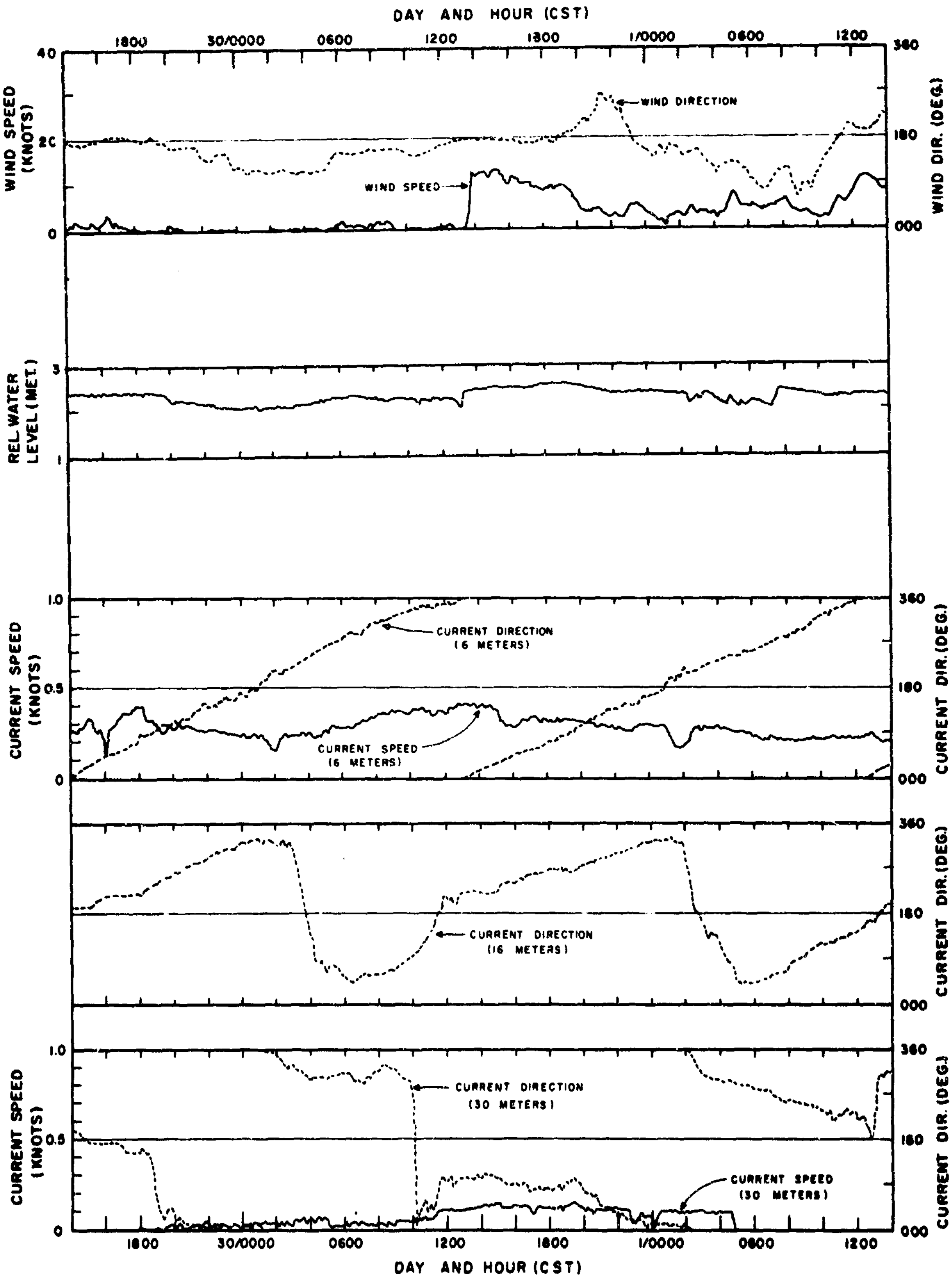
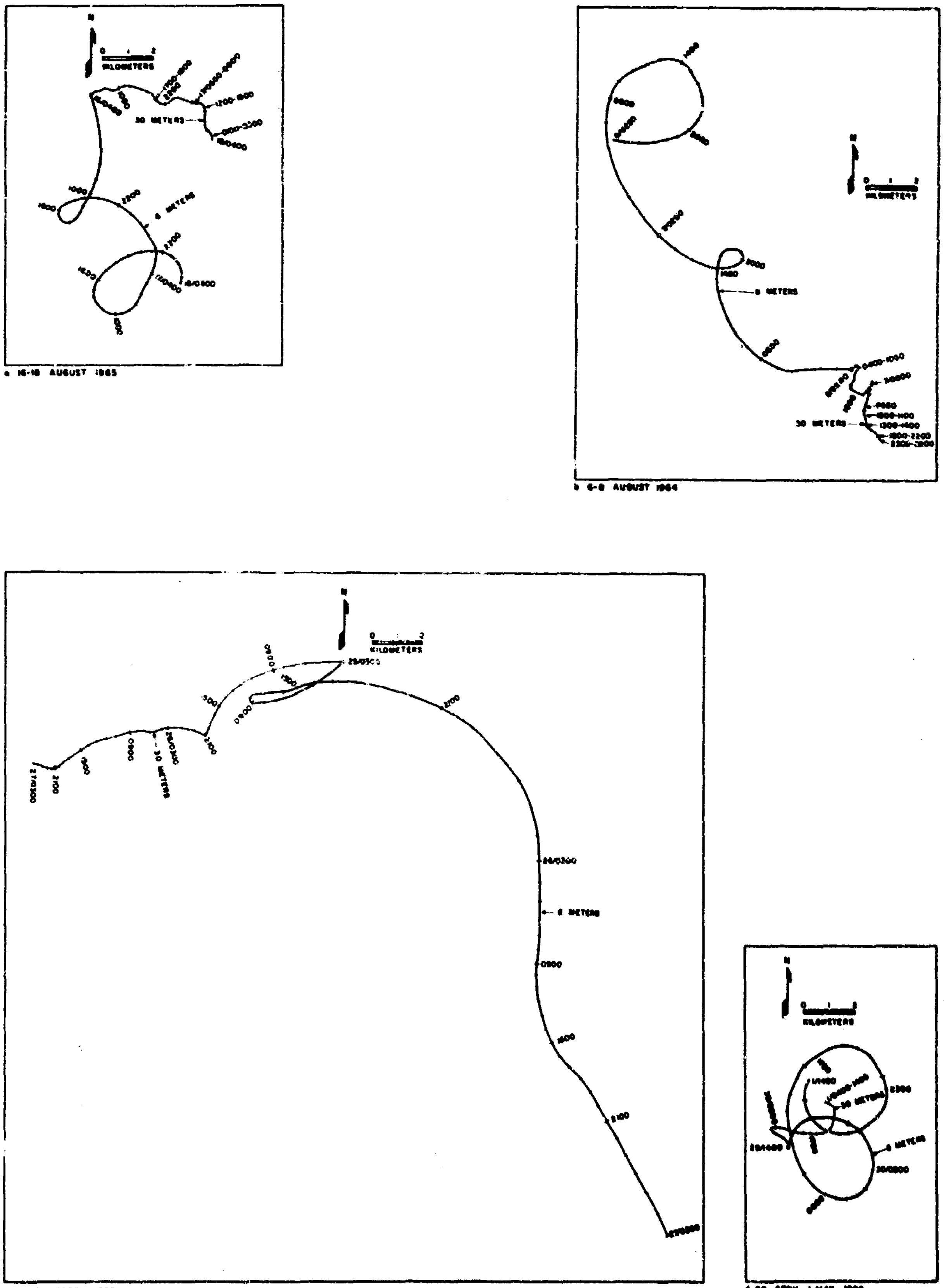


FIGURE IV-1. Example of continuous record of currents, tide and wind measured at station I, 29 April - 1 May 1966.



a 16-18 AUGUST 1965

b 6-8 AUGUST 1964

c 23-27 MARCH 1966

d 29 APRIL-1 MAY 1966

FIGURE IV-2. Current vector displacement diagrams for station I.

Several sets of 24 hour drogue observations were made at station VIII situated at the head of De Soto Canyon (Figure I-1). A comparison of vector displacement diagrams between I and VIII for the same 24 hour period is given in Figure IV-3. The steady drift components in the surface layer differ by about 45 degrees (which coincides well with orientation of isobaths) but both exhibit the same rotational tendency and speeds are comparable. In contrast, the bottom drift at I is southerly compared to the easterly drift at VIII and drift speed at I is about one-fifth that at VIII. This suggests an onshore component of bottom water movement somewhere between the two stations and spreading along the isobaths. Data taken at VIII are too sparse to characterize the circulation except to note that surface water rotation is qualitatively similar at I and VIII, that bottom current directions at VIII tend to be either easterly or westerly and that larger ranges of current speeds have been encountered at VIII.

A third example of tidal currents is illustrated in Figures IV-4 and IV-5. The parachute drogue trajectories were obtained at station A13 on the Panama City transect at a water depth of about 550 meters. As will be shown later, this position happened to be in the center of an eddy so the quasi-steady current component was small enough to permit good measurements of the tidal component. Note that different distance scales are used on the three parts of IV-4. The north components of current velocity at the three nominal depths are plotted in Figure IV-5. The diurnal tidal component is obvious and it is noteworthy that there is not a pronounced phase difference between levels. Thus, the internal tide appears to be negligible. The speed range of the diurnal tide (barotropic flow) varies from about 0.4 meters per second near the surface to 0.2 meters per second from mid-depth to near the bottom.

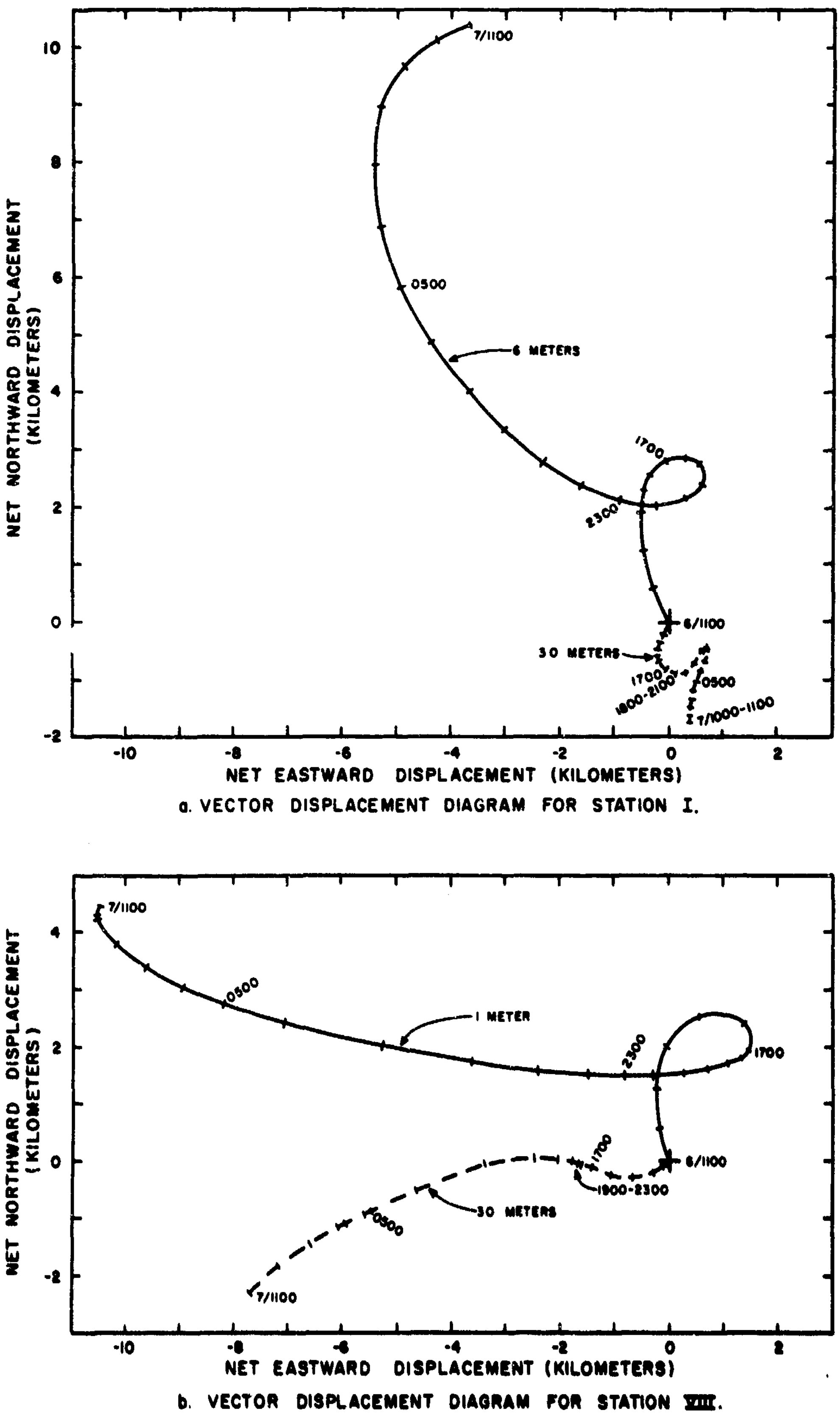


FIGURE IV-3. Comparison of vector displacement diagrams for stations I and VIII, 6-7 August 1964.

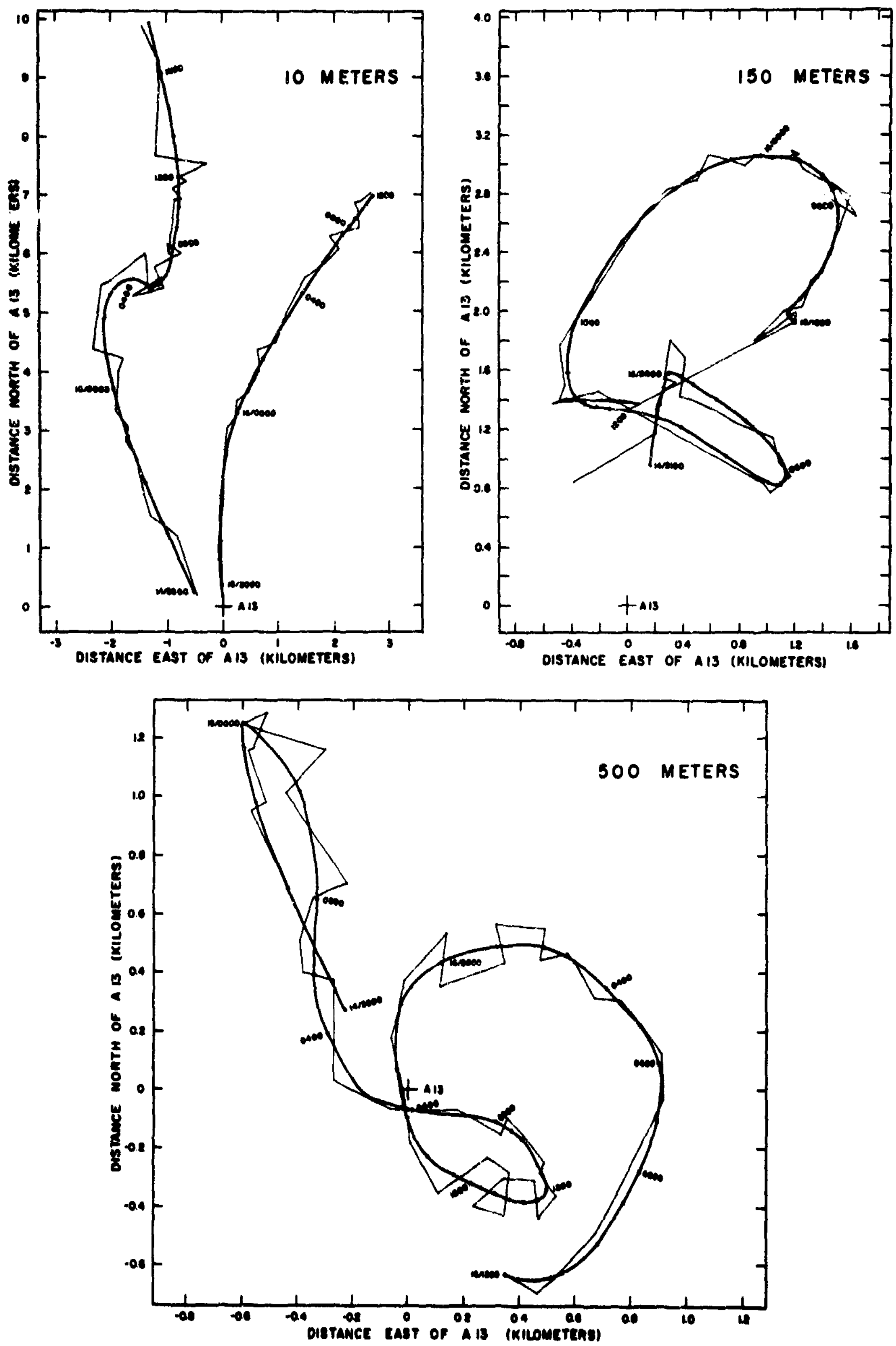


FIGURE IV-4. Parachute drogue trajectories at station A13, 14-16 April 1966.

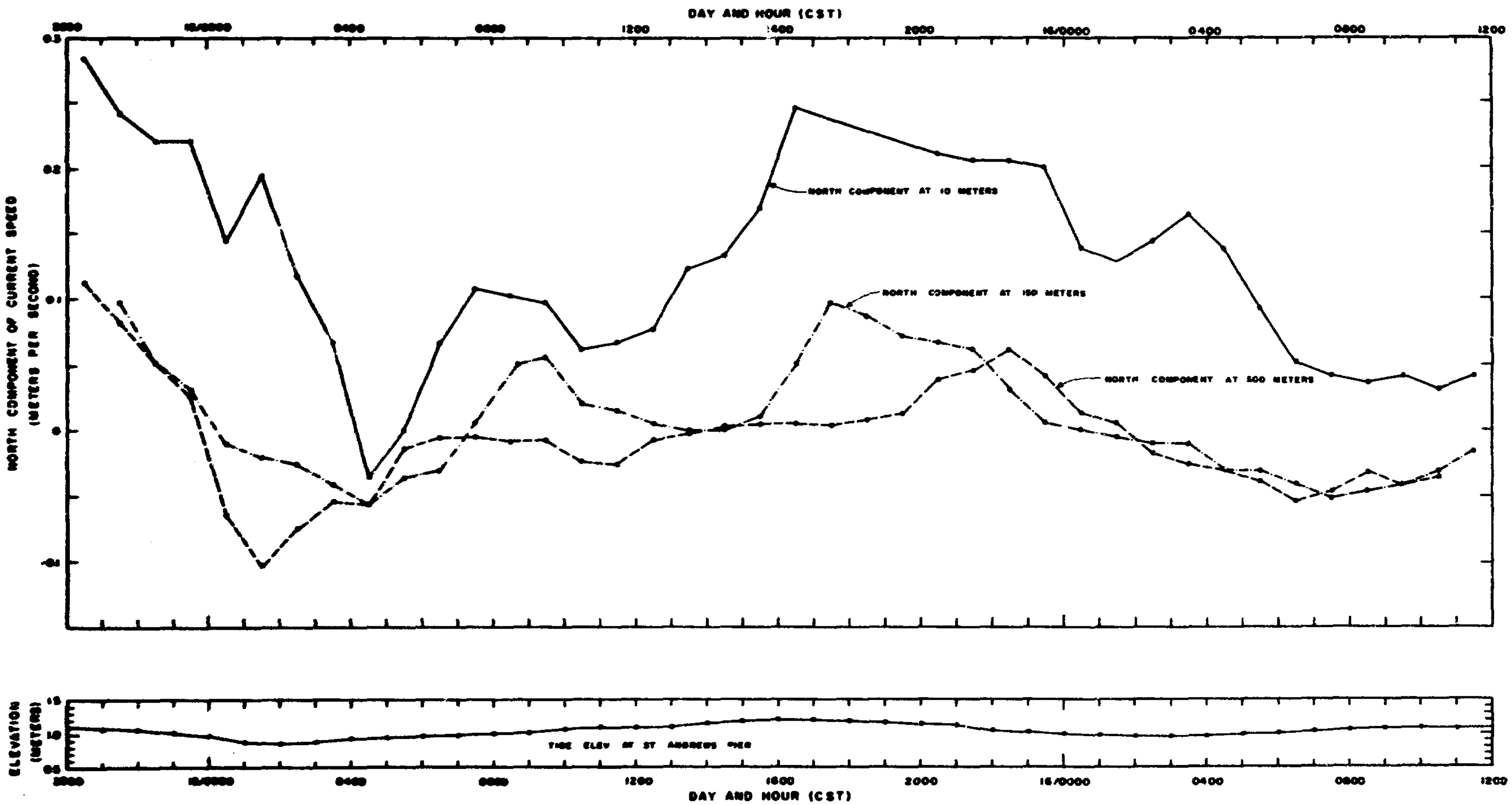


FIGURE IV-5. North component of parachute drogue velocities observed at station A13, 14-16 April 1966.

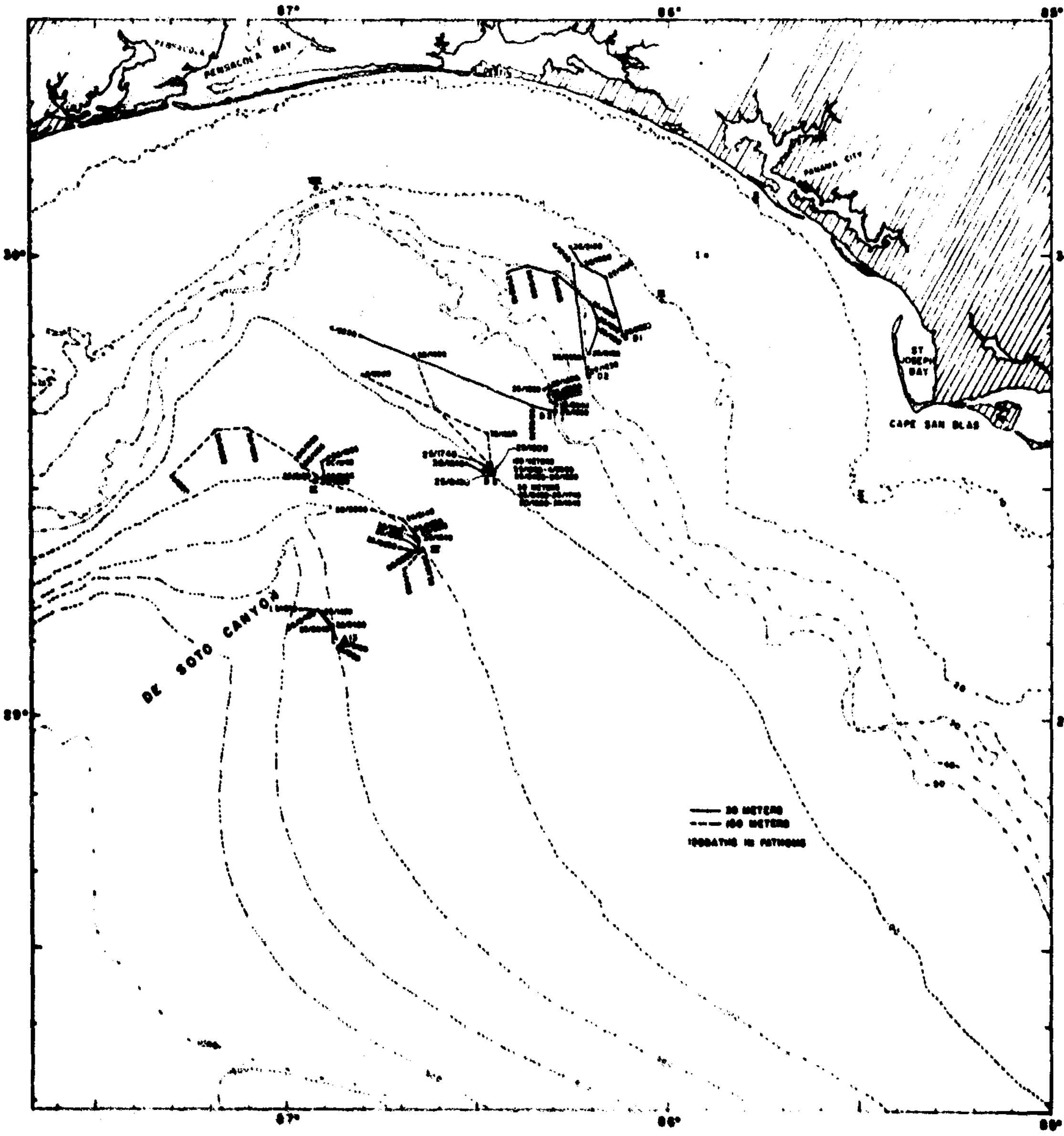


FIGURE IV-6. **Parachute drogue trajectories during 25 April-4 May 1966.**

C. Quasi-steady Currents

1. Parachute drogue trajectories. Some mention of quasi-steady currents at station I and VIII has been made in discussion of Figures IV-2 and IV-3. A series of particularly interesting parachute drogue observations were made in deeper water in the spring of 1966. Three sets of trajectories embracing a period of seven weeks have been chosen to typify observed flow patterns (Figures IV-6, IV-7 and IV-8).

Figure IV-6 shows trajectories of parachutes at nominal depths of 30 and 150 meters during 25 April - 4 May. Straight line segments connect dots that denote the places where drogues were positioned at the dates and times noted. Multiple releases at D2, D3 and D5 indicate no major changes in the general flow pattern over the monitoring period. Flow is conspicuously cyclonic following the general trend of the contours.

Figure IV-7 is for the first seven days of June. In just four weeks the flow is seen to have become conspicuously anticyclonic outside the break between shelf and slope with a well defined eddy centered at A13 and extending well below 150 meters. The diameter of the eddy is at least 100 kilometers. The trajectories at K5 and III indicate that flow along the shelf is northwestward or westward across the isobaths.

By mid-June the flow regime has again changed significantly as can be seen in Figure IV-8. The well defined eddy centered at A13 has given way to an easterly drift that appears to be most intense between A13 and A15. There is some hint of an eddy centered somewhere south of A15. Westward flow appears to prevail across De Soto Canyon as well as outside the shelf south of the Mississippi delta.

2. Net drift vectors. Net drift vectors representing virtually all of the data available from this study are

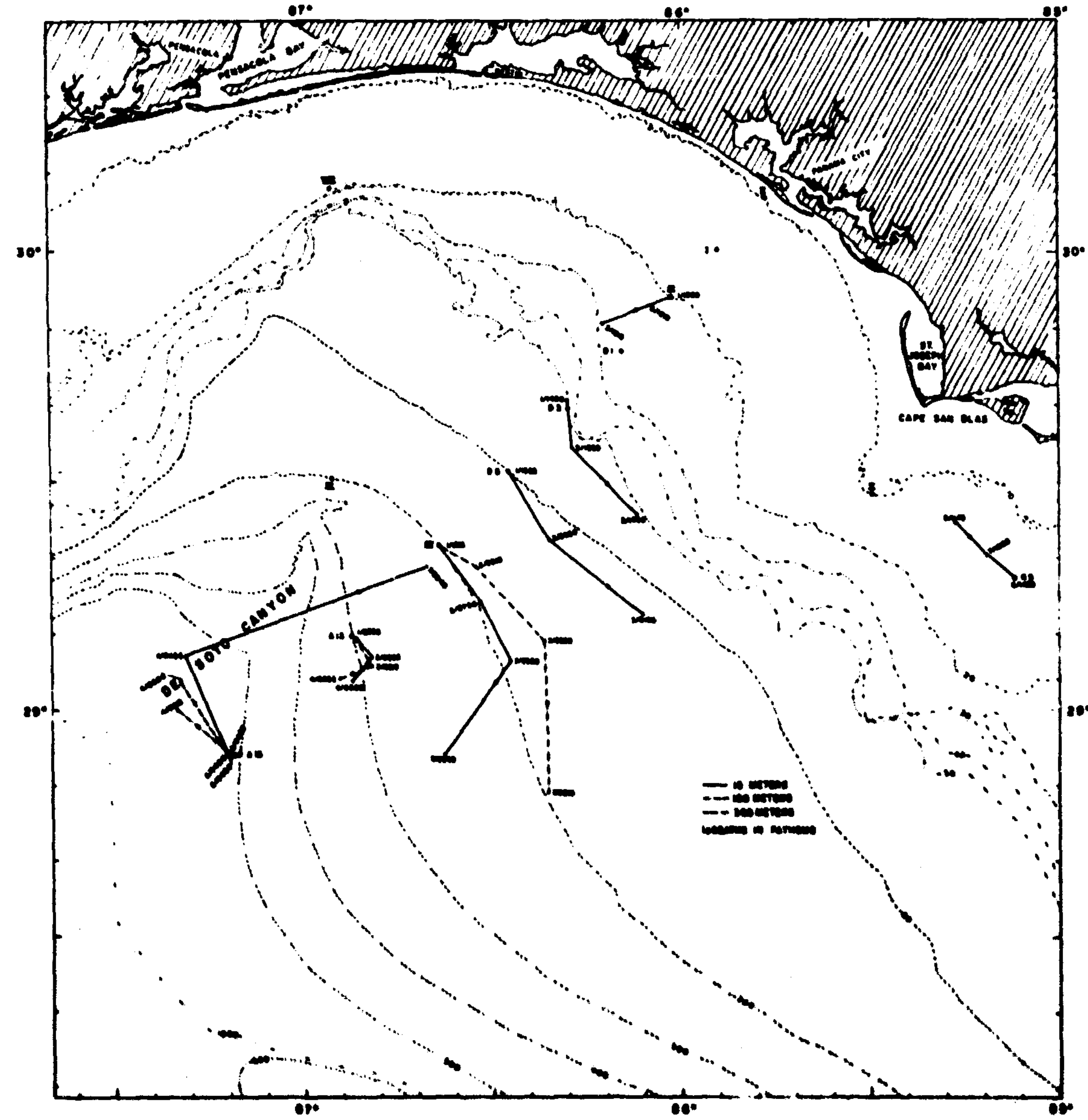


FIGURE IV-7. Parachute drogue trajectories during 1-7 June 1966.

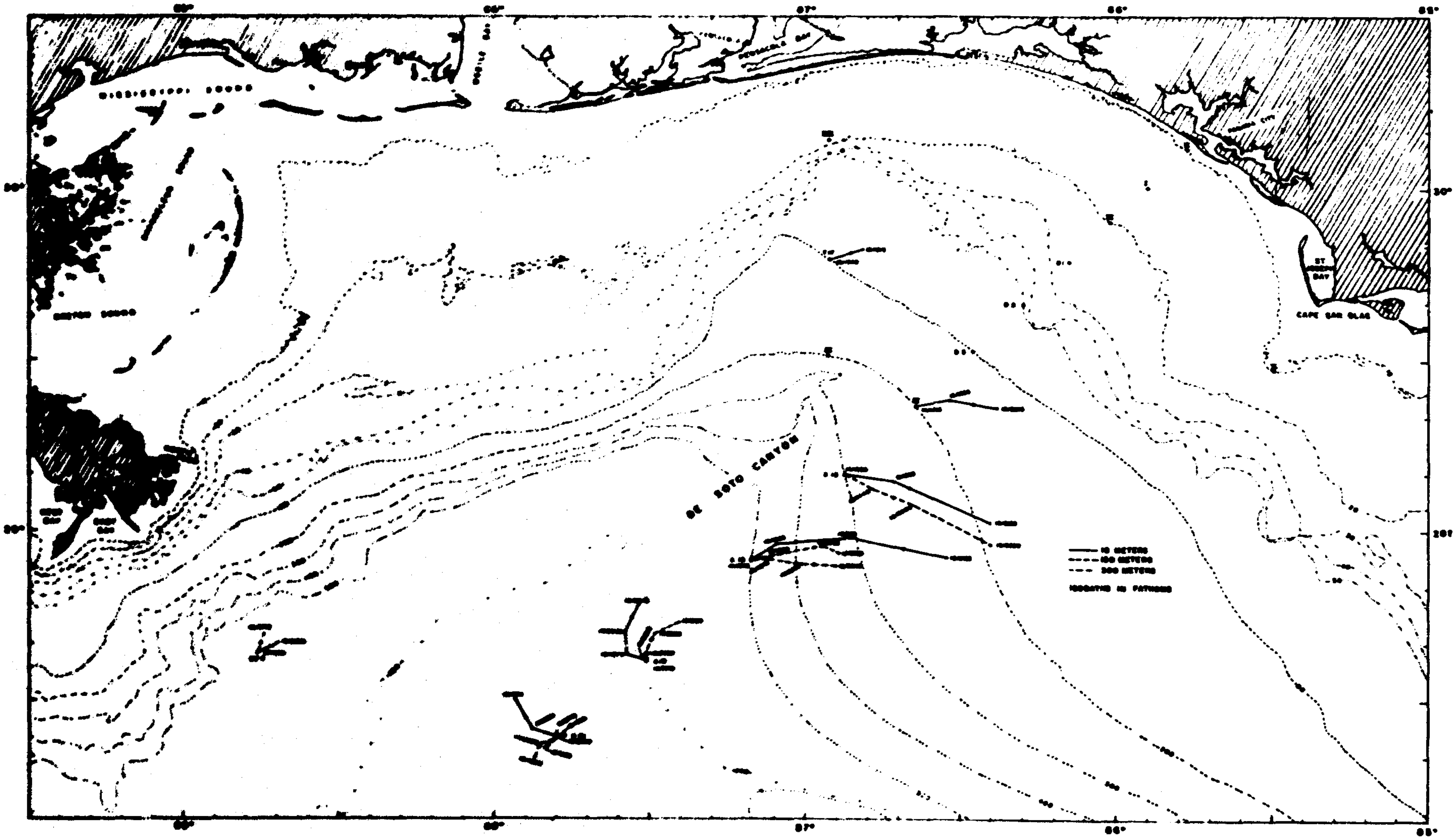


FIGURE IV-8. Parachute drogue trajectories during 14-19 June 1966.

tabulated in Appendix D. The examples illustrated below were selected on the basis of areal coverage adequate to give a coherent spatial representation. Two of the four cases chosen are derived from the trajectories shown in the previous section and all are in the period March - June 1966.

Net drift velocities observed during 22-31 March 1966 are shown in Figure IV-9. Flow at A15 is northwestward at all three observation levels and speeds range from about 0.35 meters per second in the surface layer to 0.17 meters per second at 500 meters. Currents at IX and IV are eastward in the upper 150 meters and southeastward at D5 with surface layer speeds up to 0.7 meters per second (based on 12 hours of drift). The relatively high surface speed at D5 might be a manifestation of convergence between the onshore component of flow indicated at IX and the offshore component over the shelf indicated by the 30 meter vector at I. A similar occurrence was suggested by the trajectories for 1-7 June (Figure IV-7). Bearing in mind that the measurements were spread over a ten day period, the results suggest an anticyclonic eddy or loop which is open to the southeast, centered in the vicinity of A13 and bounded on the north by the edge of the continental shelf.

Observations made two weeks later over a two day period are shown in Figure IV-10. A striking feature is the strong barotropic shear flow measured at A19*. The currents at 10, 150 and 500 meters were remarkably constant in speed and direction over the 20 hour observation period. In contrast to the strong flow at A19*, net drift below the surface layer at A15 is negligible even though the distance between stations is less than 100 kilometers. Superposition of IV-10 on IV-9 would produce a consistent pattern wherein the northward sub-surface flow past A19* is deflected towards the northeast by the continental slope presumably to swing further westward as it approaches the west side of De Soto Canyon. The flow in

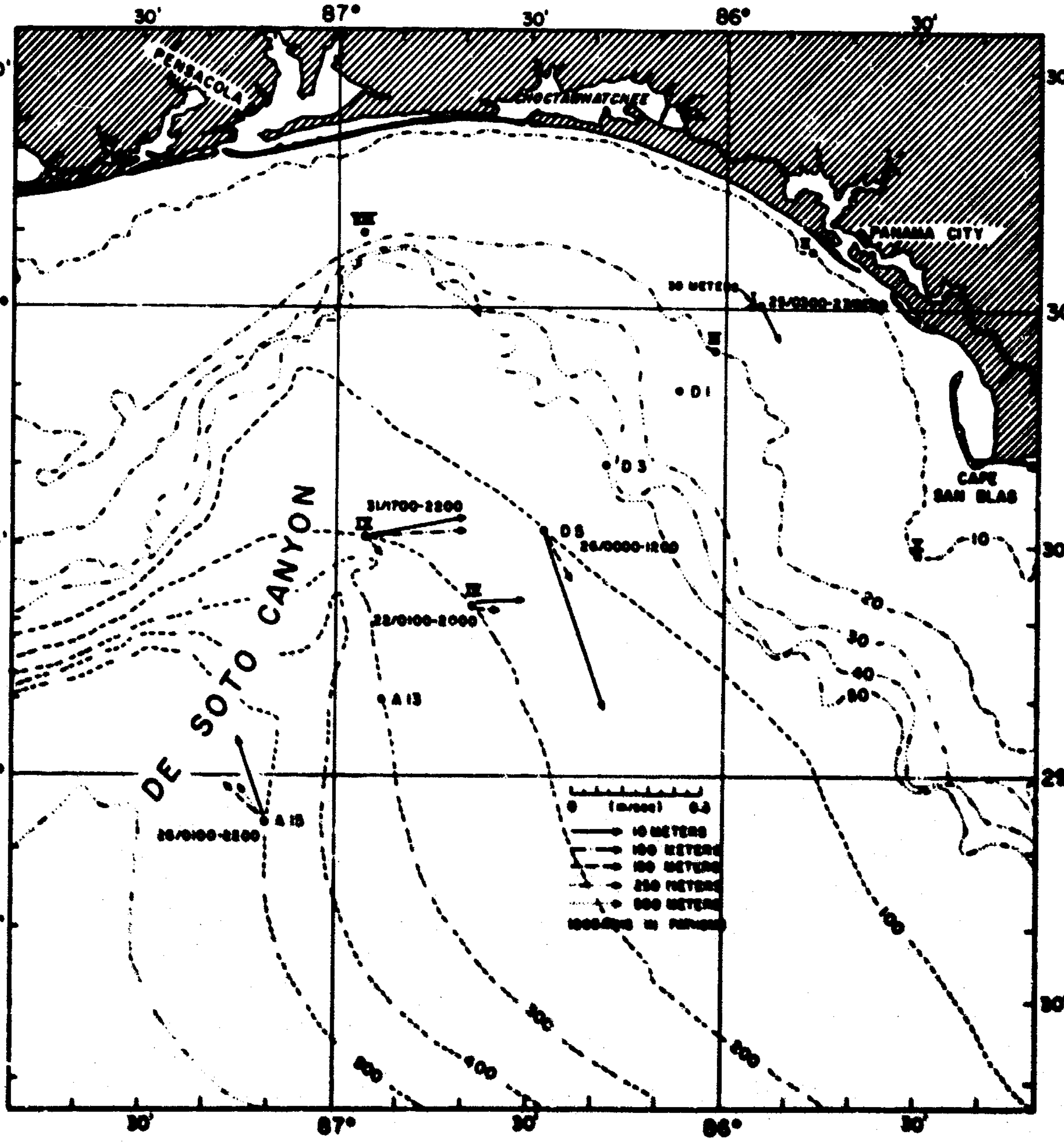


FIGURE IV-9. Net drift vectors based on current measurements made during 22-31 March 1966.

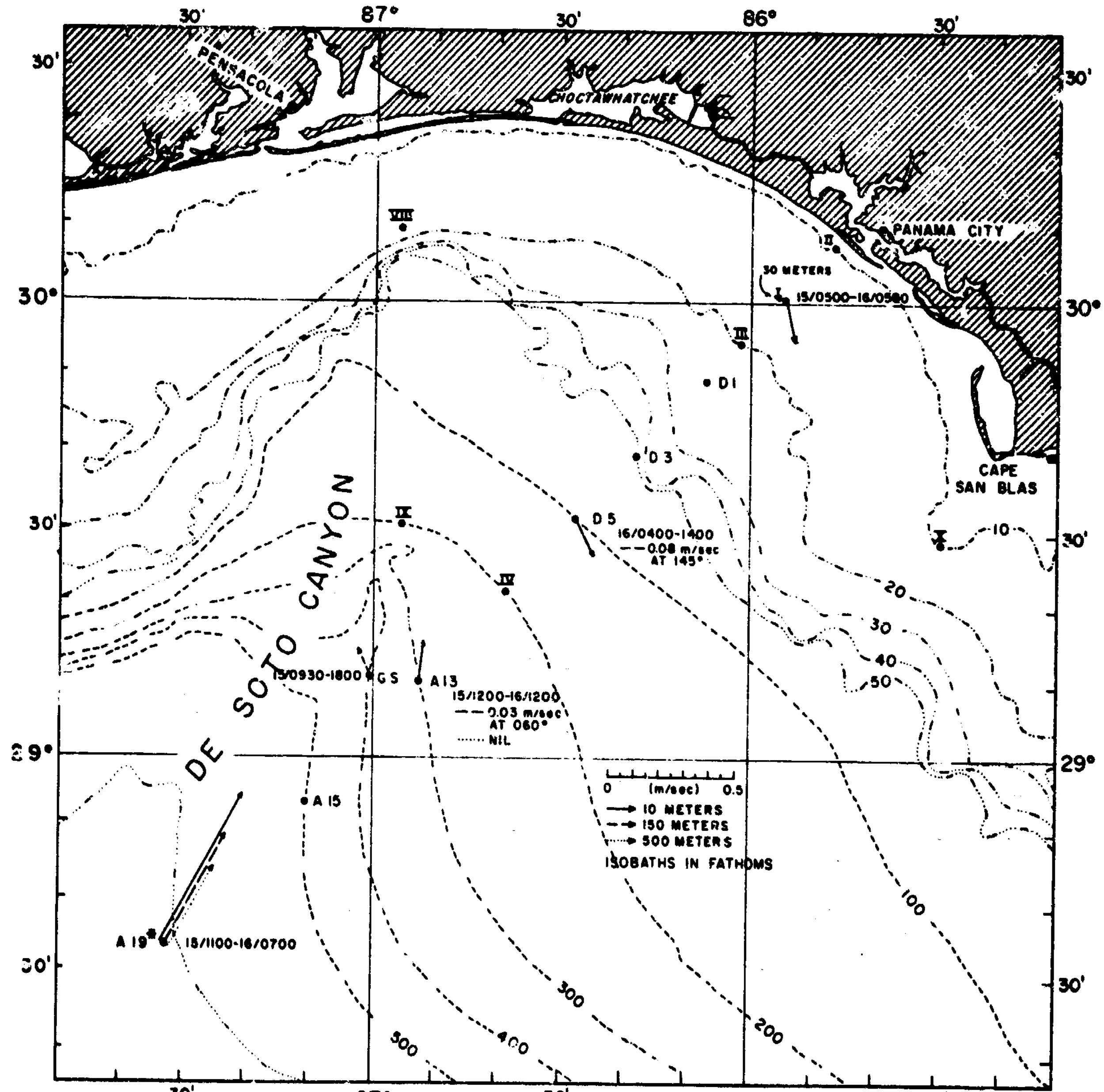


FIGURE IV-10. Net drift vectors based on current measurements made during 15-16 April 1966.

the upper 50 to 200 meters (surface layer) appears to turn to the right over the canyon and form an anticyclonic eddy or loop centered near A13.

Figure IV-11 gives net drift vectors for the period 2-7 June. The flow orientations at stations outside the 50 fathom isobath are consistent with the above interpretation of Figures IV-9 and IV-10. A conspicuous feature is the horizontal shear between westward flow over the shelf and southeastward motion of the surface layer further offshore. Thus, there appears to be an intensification of southeastward flow between D3 and IV due to convergence of shelf and offshore surface waters.

A final example of net drift vectors is given in Figure IV-12 for the period 15-29 June. These results reveal weak drift at A19 and A41 whereas at A15 and A13 the currents are westward throughout the water column at speeds of 0.1 to 0.3 meters per second. It is apparent that the general circulation which seemed reasonably steady for over two months underwent a significant transition within three weeks in June.

3. Geostrophic currents. The dynamic method of computing geostrophic currents has been well known since the turn of the century and is thoroughly documented, e.g., Sverdrup, Johnson and Fleming (1946) and Fomin (1964). The method has not been used widely for circulation studies in recent years because of its critical dependence on selection of a "reference level," at which there is assumed to be essentially no motion, in order to estimate absolute velocities. Uncertainty is increased near rigid boundaries because of the boundary layer which can introduce forces other than those due to the horizontal pressure gradient and rotation of the earth.

The average geostrophic current, u, normal to a vertical plane between two positions separated by a horizontal distance, L, and in a layer bounded by an upper pressure surface, p_1, and

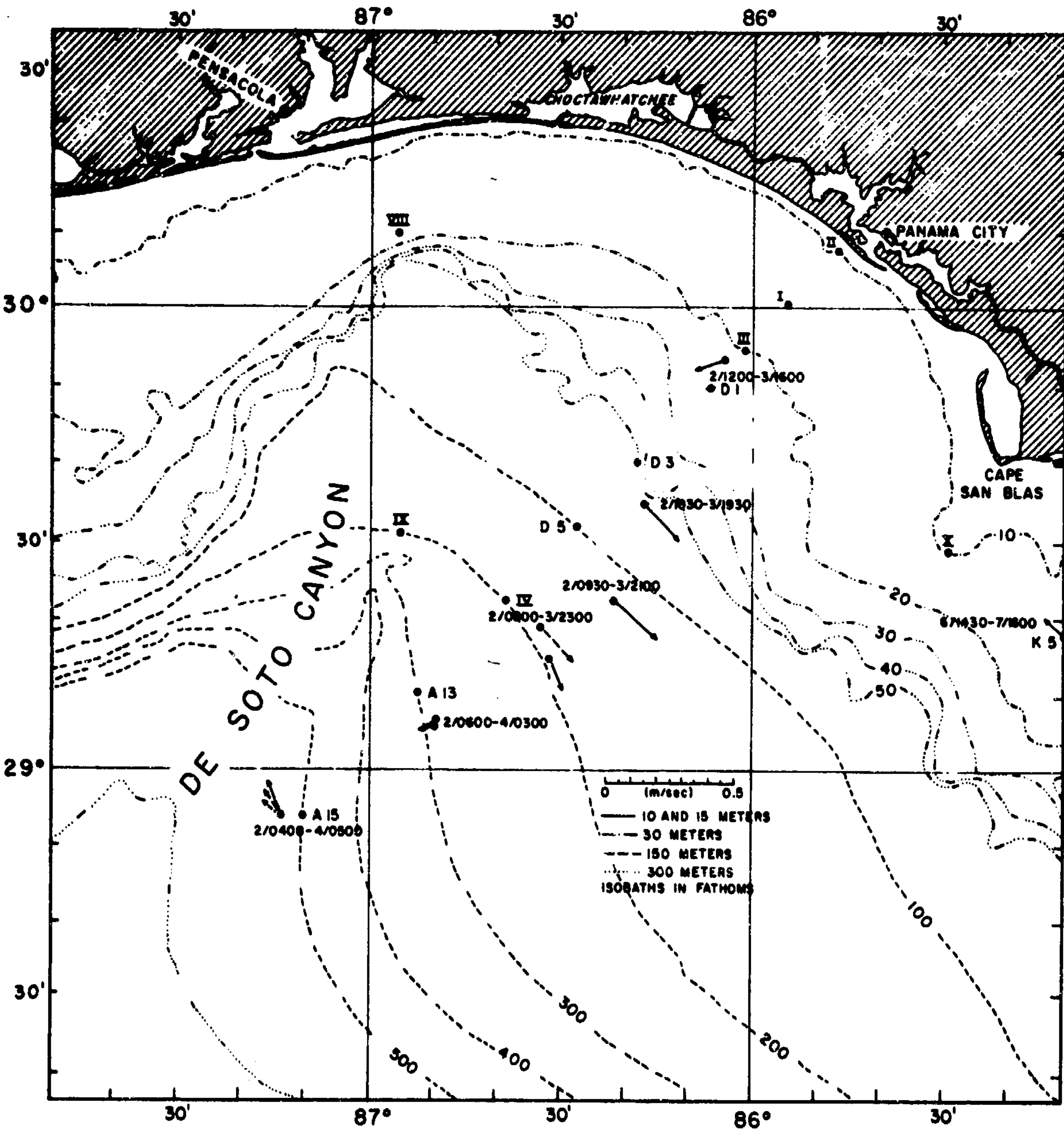


FIGURE IV-11. Net drift vectors based on current measurements made during 2-7 June 1966.

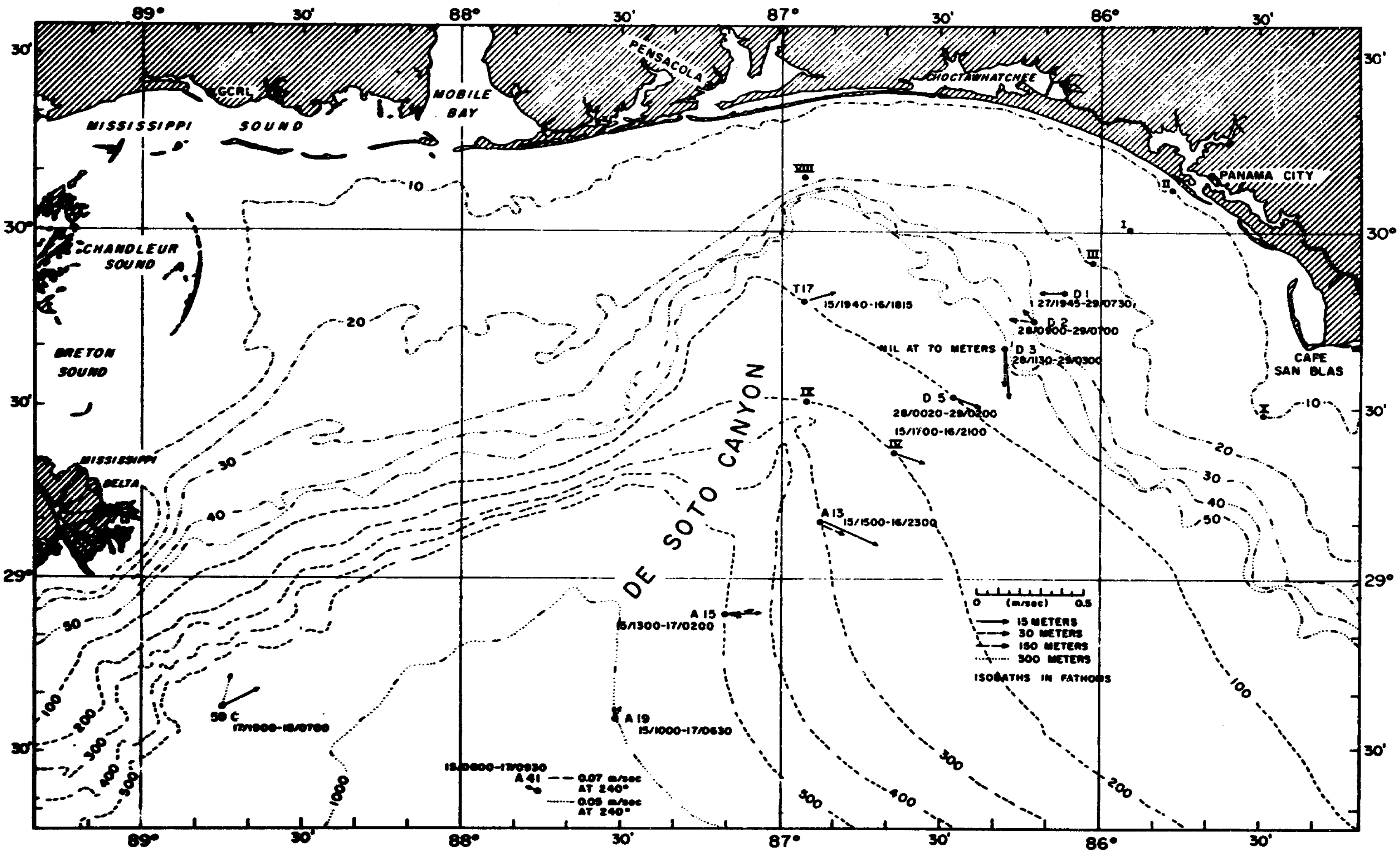


FIGURE IV-12. Net drift vectors based on current measurements made during 15-29 June 1966.

a lower pressure surface, p_2, is given by

$$u = \frac{D_a - D_b}{2\omega L \sin \phi} \qquad \text{(IV-1)}$$

where D_a and D_b are the dynamic height anomalies at the positions, a and b, at the termini of L, ω is the angular speed of the earth's rotation and ϕ is the average latitude. The dynamic height anomaly at a particular location is given by

$$D = \int_{p_2}^{p_1} \delta \, dp \qquad \text{(IV-2)}$$

where p is pressure and δ is thermosteric anomaly. As shown by Montgomery and Wooster (1954), δ may be replaced by δ_{st} in (IV-2) without significant loss of precision for computations applicable to the upper several hundred meters. For convenience, 30 degrees was taken as the latitude for all computations of current speed. Denoting the difference in dynamic heights at adjacent stations as ΔD and inserting the constant, $\omega = 0.729 \times 10^{-4}$ radians per second, Equation (IV-1) becomes

$$u = \frac{137(\Delta D)}{L} \qquad \text{(IV-3)}$$

where L is in kilometers, ΔD in dynamic meters and u in meters per second.

Cautious application of the dynamic method can produce good qualitative representations of the velocity field even for small scale nearshore features as has been demonstrated, for example, in a set of observations by Reid, Schwartzlose and Brown (1963). It should be noted that the method yields estimates of shear between two horizons; therefore, good indications of relative currents are obtainable irrespective of the level of no motion.

The matter of extending dynamic computations inshore when the lower reference level intersects the boundary has been a

major cause for concern. Fomin (1964, pp. 150-155) summarizes four proposed methods for artificial extension of the reference level into the boundary. The method used in this study dates back to 1885 wherein the isanosteres simply are projected horizontally into the boundary from the point of intersection.

An example of the relative flow over the continental slope between 50 and 200 meters is shown for December 1965 in Figure IV-13. The characteristic eddy centered near A13 is evident but the flow is cyclonic. The current speed in the band bounded by dynamic anomalies of 0.25 and 0.27 is quite uniform as it turns westward beyond station XII. A current speed of about 0.2 meters per second is obtained from Equation (IV-3).

It is of interest to compare the circulation indicated by Figure IV-13 with the situation discussed previously based on the section from M99 to IV (Figure III-12). The distribution along the section of geopotential anomaly at the sea surface relative to the 27.6 isanostere (average depth of about 900 meters) is shown in Figure IV-14. The supposition that the circulation has an onshore component between M99 and A1 and an offshore component between A1 and A8 is substantiated by the geopotential anomaly distribution. If an eddy existed over A13, the main flow suggested between A1 and A8 would require that the eddy be cyclonic as is the case a month later according to Figure IV-13. Considering the similarity of the two sections run in October and November from off the Mississippi delta to Panama City, the extension of the comparison to December may not be unreasonable.

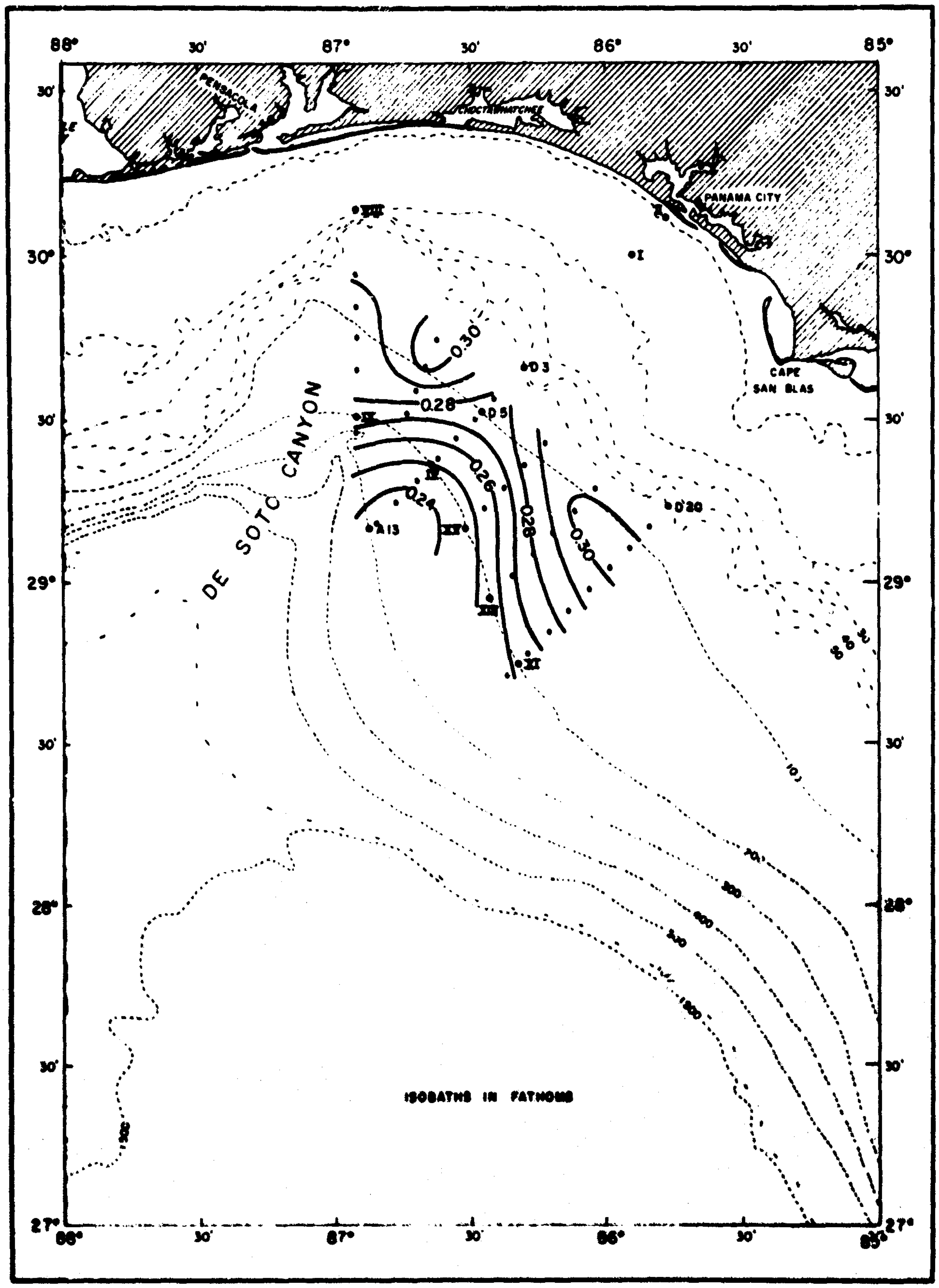
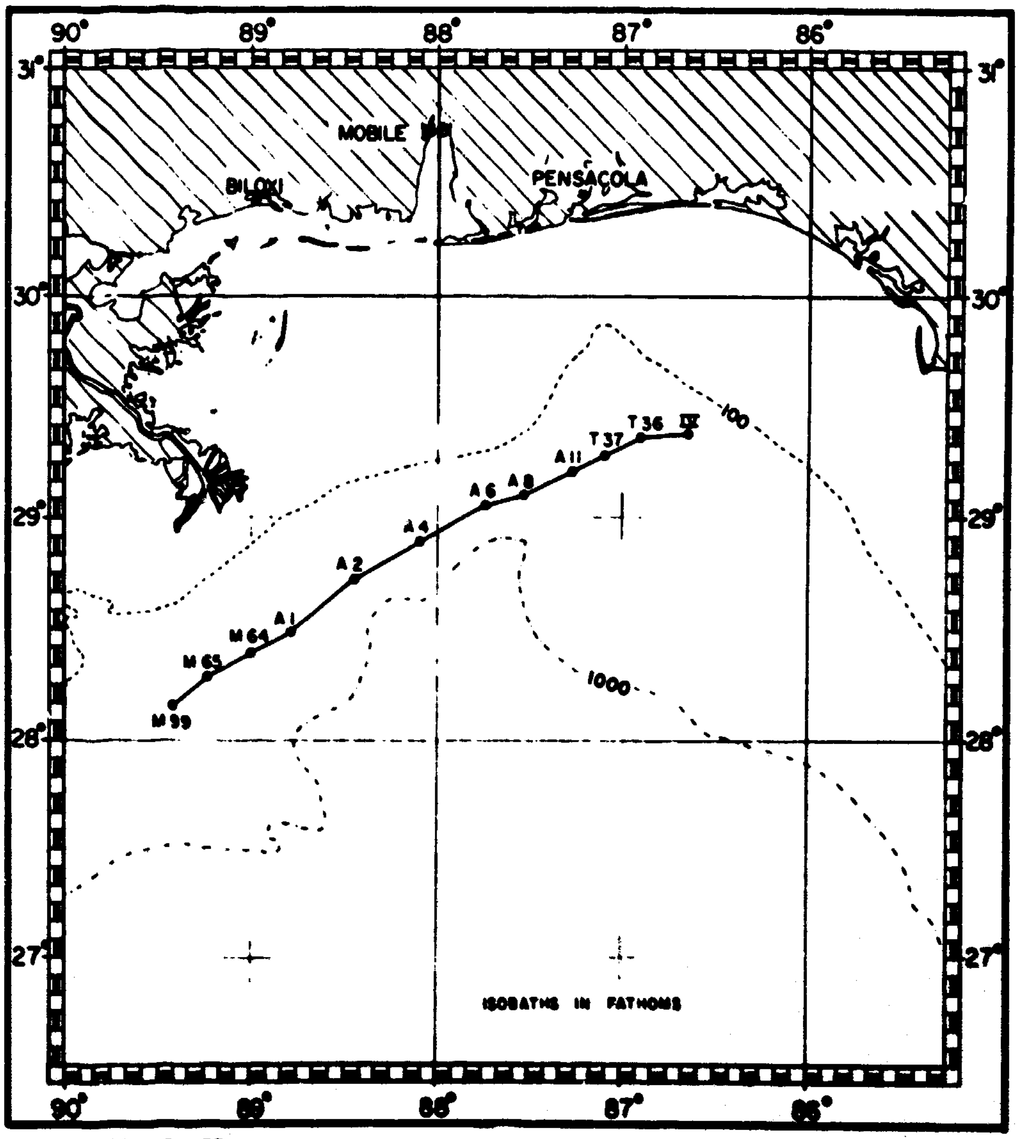


FIGURE IV-13. Geostrophic flow during 13-17 December 1965 based on dynamic anomalies at the 50 decibar surface relative to 200 decibars.



a. TRACK CHART

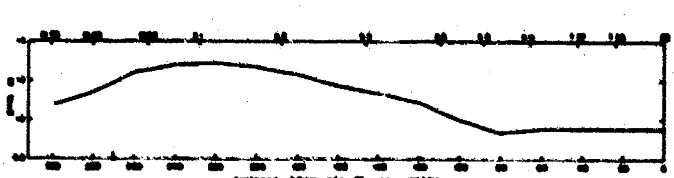


FIGURE IV-14. Geopotential anomaly along the section from M99 to IV, 15 November 1965.

V. DISCUSSION AND CONCLUSIONS

The rather extensive set of hydrographic and current observations made during the three years beginning in 1963 by no means are comprehensive in relation to the character and variability of circulation over the northeast boundary of the Gulf of Mexico. The preceding summary of these observations has been aimed at highlighting critical features that might contribute to an overall understanding of the circulation. The usual step of estimating water mass transports has been omitted because of the paucity of quantitative data. A major outcome of this study could be provision of a descriptive foundation for designing future investigations of circulation in the Gulf of Mexico.

A. Dominant Circulatory Features

1. Influence of the loop current. There can be little doubt of the continuous influx of water through the Yucatan Channel and northward into the center of the Gulf. The relative magnitudes of transport to the Florida Straits via a nearly direct path at latitudes below 25 degrees versus the anticyclonic "loop" which may extend northward to the continental boundary between the Mississippi delta and Cape San Blas are a matter of speculation. Neither has the existence of multiple eddies been demonstrated or disproved. Almost certainly the intensity and configuration of flow around the loop is quite variable over a wide temporal span.

If the main impetus for flow over the boundary is circulation in deep water, then the dynamical nature and geographic distribution of the loop current is of primary concern. In Figure V-1 are shown contours of the depths (in meters) of the 22°C isotherm based on bathythermograph data taken in June 1966. The anticyclonic single loop is clearly evident as is a northward extension to at least the 28th parallel. In the winter

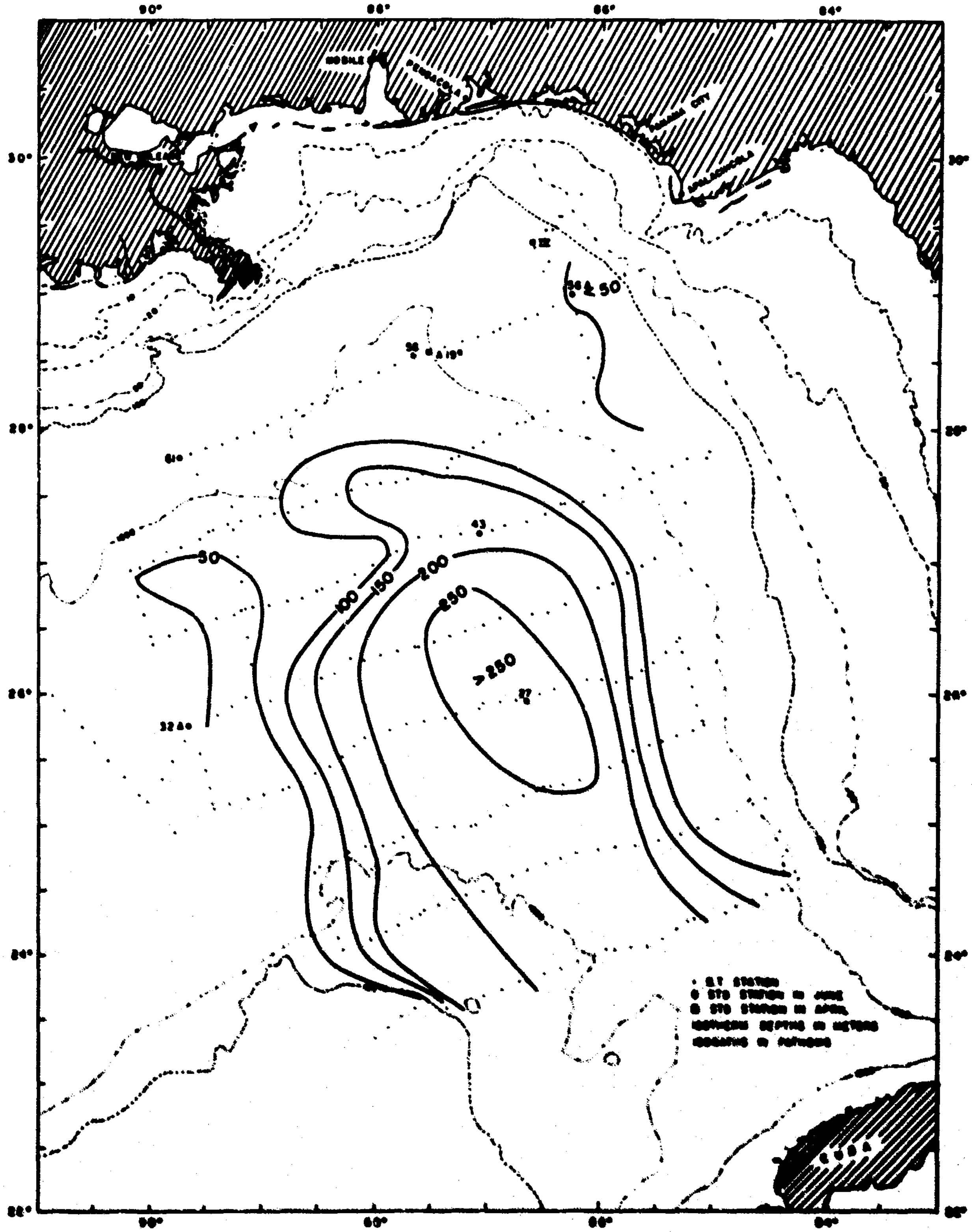


FIGURE V-1. Contoured depths of 22°C isotherm based on BT data at positions shown during 5-22 June 1966.

of 1962 the north limit of the loop was observed to be one or two degrees of latitude further south (Nowlin and McLellan, 1967). Neither G.E.K. measurements nor dynamic height topography revealed the presence of well defined currents north of the loop in 1962 or 1966.

Nowlin and McLellan (1967) have found that the center of the loop current has a distinctive T-S relation differing little from the characteristic relation for mainstream waters flowing through the Yucatan Channel. The relation is characterized by a salinity maximum greater than 36.7‰ between 20°C and 24°C. Examples of center loop water sampled at stations 27 and 43 (Figure V-1) are shown in Figure V-2. The alteration of the T-S curve northward is evident in the form of marked reduction in the salinity maximum, presumably due to entrainment and mixing of dilute waters to the north and west.

The T-S curves shown in Figure III-13 for stations A1 and A2 taken in November 1965 reveal salinity maxima of 36.64‰ and 36.60‰, respectively. These values are surprisingly close to the 36.7‰ limit characteristic of water in the center of the loop and strongly suggest that on this occasion the flow through the Yucatan Channel indeed was extending to the northeast Gulf boundary. The pronounced influence of such flow on the boundary circulation is readily inferred from Figures IV-13 and IV-14.

2. Stratified flow. There is ample evidence that the stratified water mass is characterized by vertical gradients in the horizontal velocity field. From measurements made in deeper water, it appears that the shear tends to be aligned with the direction of transport, cf. Figures IV-10, IV-11 and IV-12. Observations in well stratified water over the shelf seldom indicate uniform direction of motion throughout the water column, cf. Figures IV-1, IV-2 and IV-3. The impression has been gained from SCUBA diver observations that shear is most intense where vertical density gradients are steepest,

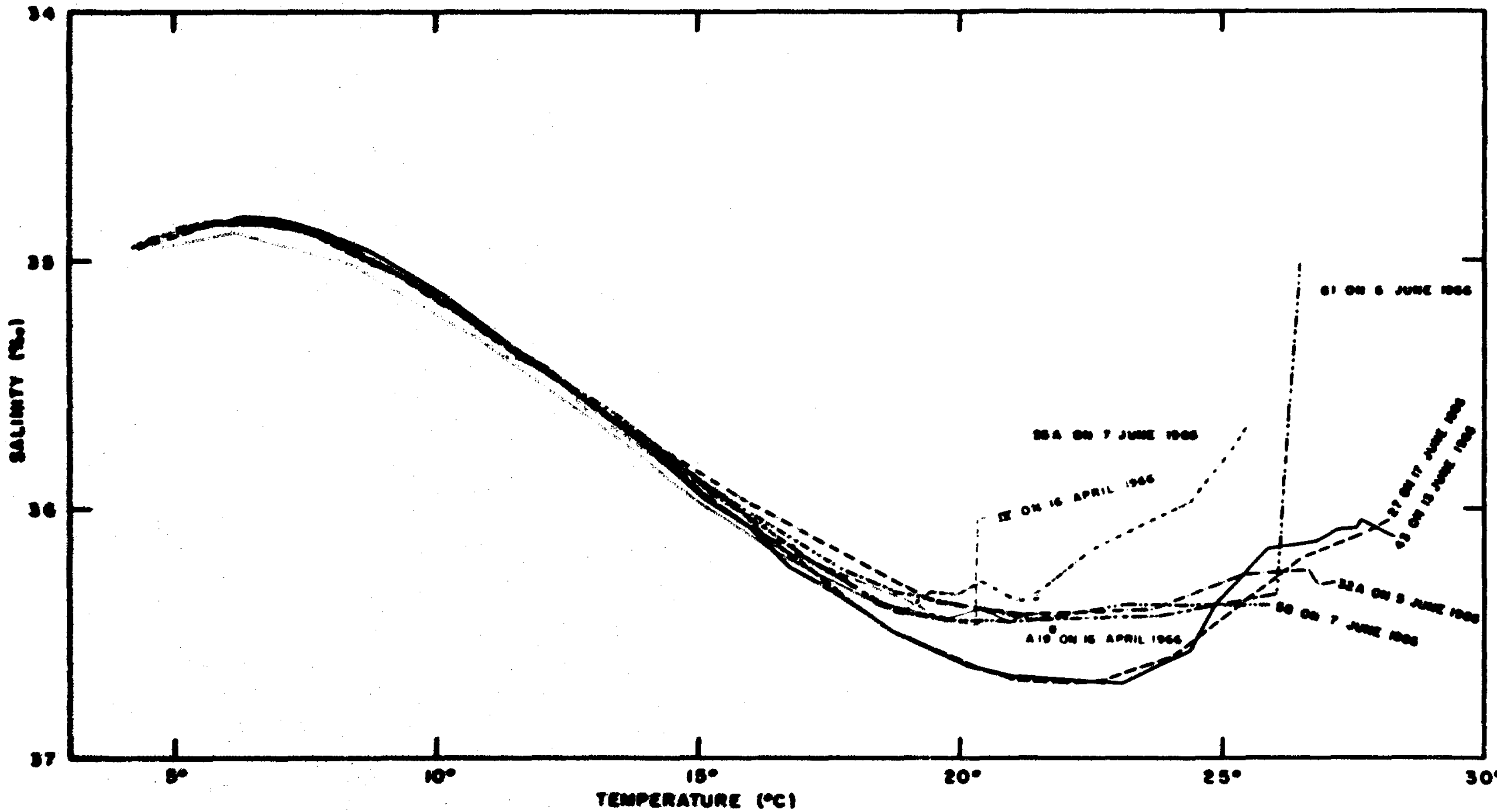


FIGURE V-2. Comparison of T-S curves northward from center of loop current in April and June 1966.

i.e., motion in the nearly homogeneous layers tends to be nearly uniform. These observations lead to the conclusion that the seasonal thermocline must have a dominant influence on circulation in the upper layers; hence, the boundary circulation, especially over the continental shelf, should exhibit strong seasonal changes even if driving forces were sensibly constant.

One aspect of the stratification deserves special attention. The very nearshore waters off Panama City have been observed to maintain a very sharp thermocline throughout the summer in spite of the obvious positive influx of net solar energy. From Table III-3, the maximum temperature observed near the bottom at station I was 26.6°C in the summer of 1965 whereas surface temperatures rarely were less than 28°C and sometimes exceeded 30°C. The values of Table III-3 also indicate a small range of variation in bottom temperature as well as salinity, e.g., August values were 1.0°C and 0.33‰, respectively. Since the thermocline is continuous both alongshore and offshore during the season, it follows that there must be a quasi-steady net transport of bottom water onshore across the shelf.

<u>3. Horizontal discontinuities and a mixing zone.</u> The common occurrence of oceanic "fronts" has been suggested by several investigators recently. Rather sharp transitions across horizontal distances of a few meters to less than ten kilometers have been encountered frequently in the work off Panama City. No effort was made to quantitatively investigate these phenomena beyond accounting for "noise" introduced in local variations due to possible advection of such features past a particular station. However, casual observations indicate that horizontal discontinuities in the surface layer found more than a few kilometers offshore tend to be aligned with the bottom topography, are continuous over distances of a few kilometers or more and typically are associated with lateral velocity shear.

One relatively large transition region appears to be semi-permanent. This is located over the break in bottom slope usually found between the 50 meter and 150 meter isobaths. Maximum spatial changes in the hydrography typically appear over this region, cf. Figures III-2, III-3, III-5 and III-6. Correspondingly, marked current shear has been found over the same region as shown, for example, in Figure IV-11. The example shown in Figure III-3 wherein the opposing sharp horizontal gradients in temperature and salinity are not reflected in the density distribution suggest that mixing is taking place along this narrow band in such a way as to maintain quasi-steady local stability.

4. Eddies over the continental slope. A repeatedly observed major circulatory feature is an eddy over the continental slope southeast of De Soto Canyon. Paradoxically, the eddy has been noted to be either cyclonic or anticyclonic and sometimes is not evident at all, cf. Figures IV-6, IV-7 and IV-8. When well defined, the eddy is centered in the vicinity of A13 and has a characteristic horizontal dimension of 100 kilometers. Further manifestations of such an eddy are given by the contoured depths of the 20°C isotherm shown in Figures V-3, V-4 and V-5. The geostrophic flow along the closed 80 meter contour in Figure V-3 would be anticyclonic whereas the flow along the 80 meter contour in Figure V-5 would be cyclonic. Significantly, there is a well defined anticyclonic loop or possible eddy shown in Figure V-4 but it is centered near the west rim of De Soto Canyon. It is also noteworthy that none of the surveys gave any indication of more than one eddy existing simultaneously over the slope between De Soto Canyon and off Cape San Blas, a distance greater than 100 kilometers.

5. A possible subsurface countercurrent. The term "countercurrent" will be construed as flow directed counter to the mass transport of the loop current. Along the northeast Gulf boundary, this would imply a westward transport. The

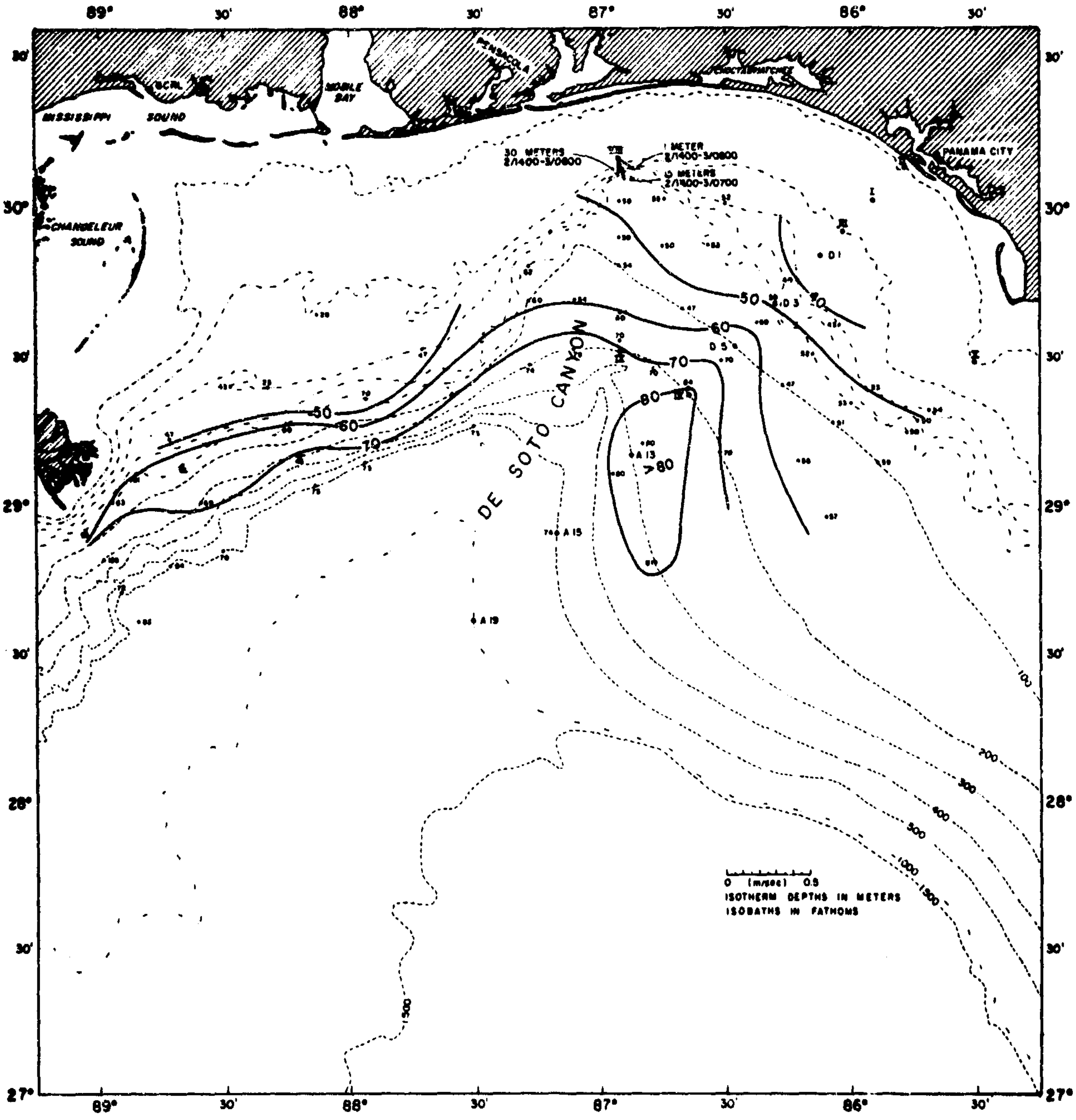


FIGURE V-3. Observed current vectors and contoured depths of 20°C isotherm, 28 June - 2 July 1964.

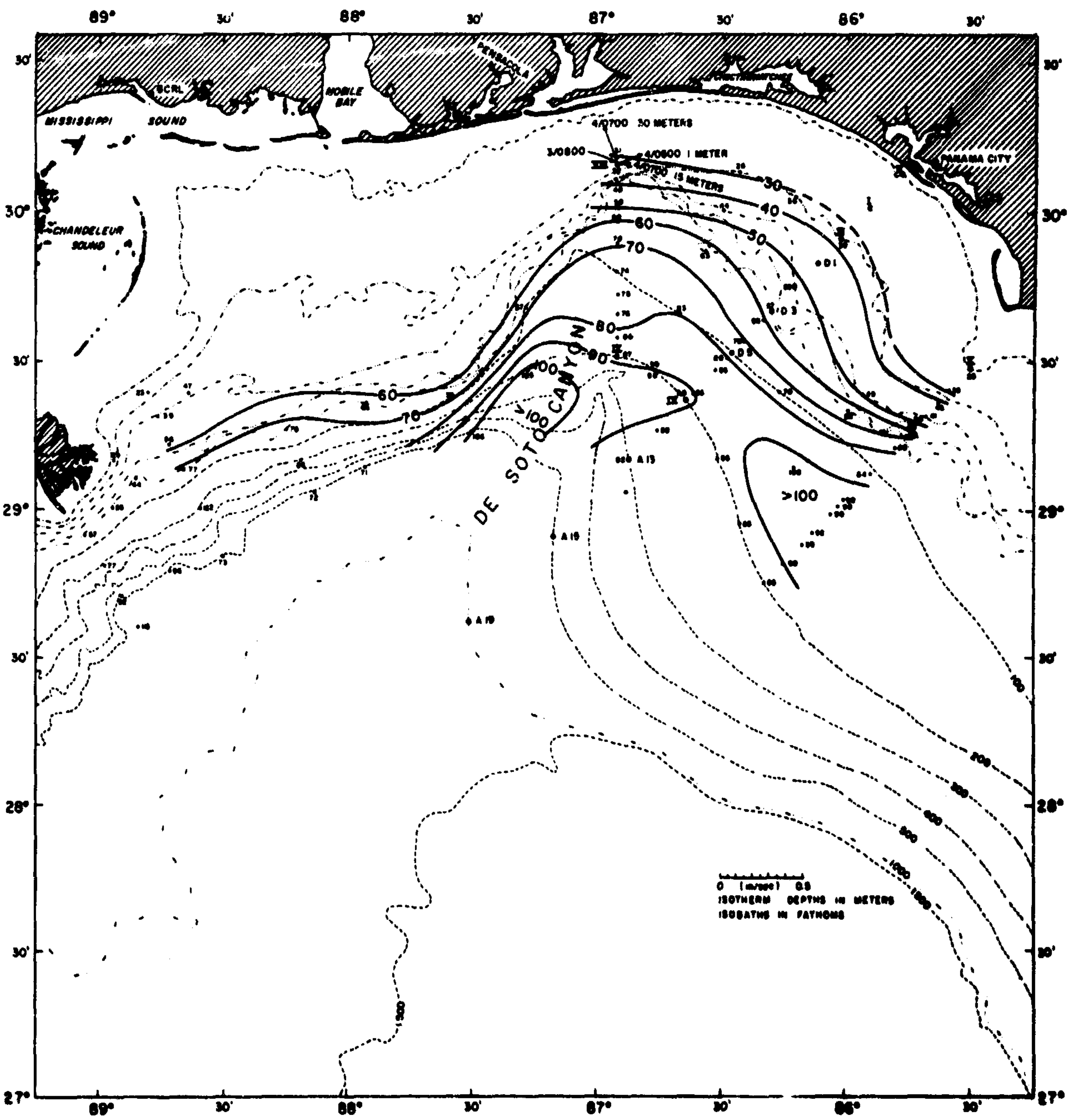


FIGURE V-4. Observed current vectors and contoured depths of 20°C isotherm, 31 August - 3 September 1964.

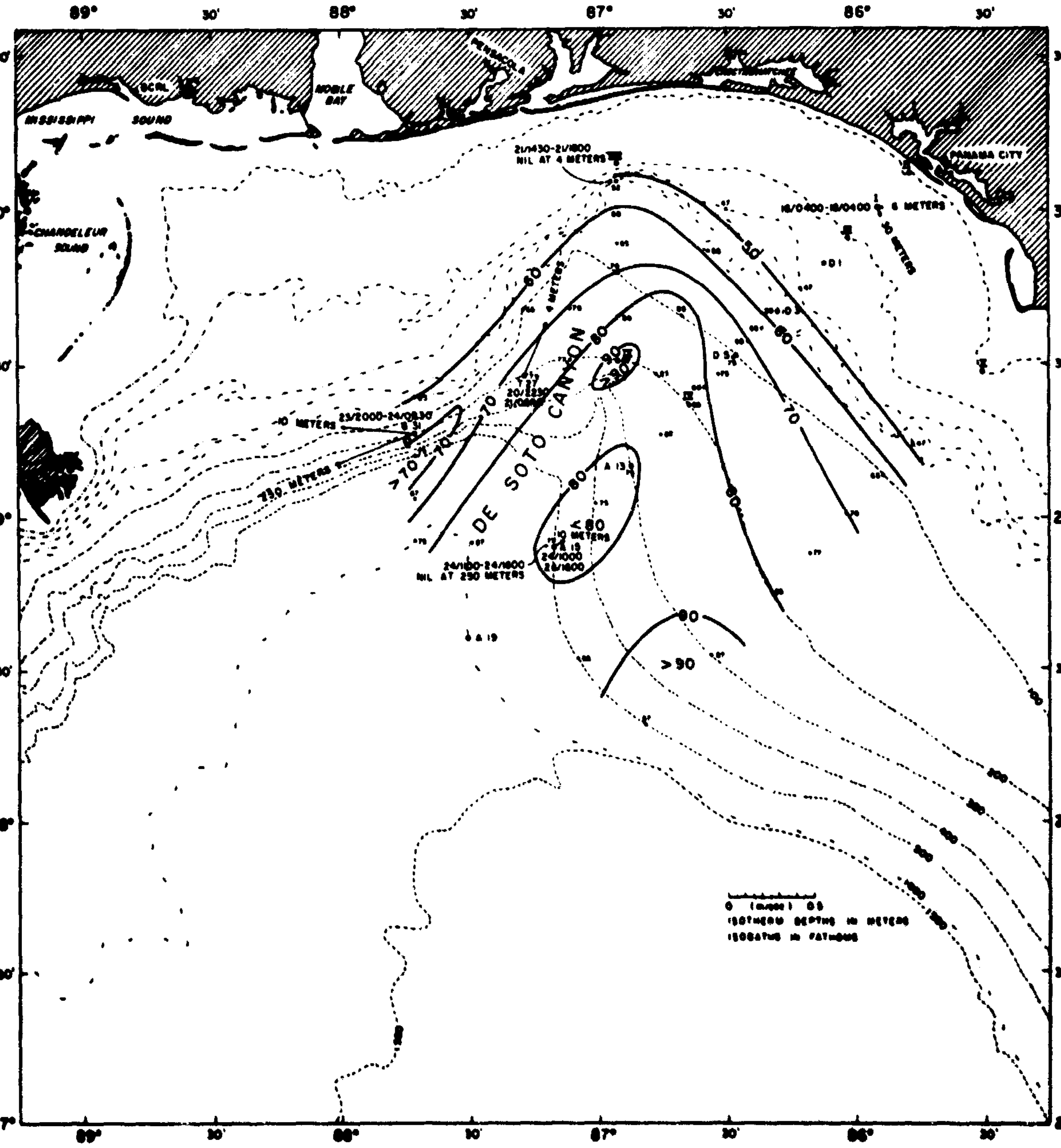


FIGURE V-5. Observed current vectors and contoured depths of 20°C isotherm, 16-24 August 1965.

term "subsurface" refers to the main body of water below the seasonal thermocline.

The observations summarized in IV-9, IV-10 and IV-11 clearly indicate a northwestward flow throughout the water column along the 500 fathom contour at station A15. It is obvious that the flow is being guided by the boundary towards De Soto Canyon. If the flow below 200 or 300 meters is not diverted to the west, then transport would have to be directed northeastward across the boundary such that very strong currents would occur in subsurface waters along the east slope of De Soto Canyon. These clearly are not evident in the direct observations. The surface water, however, does appear to circulate anticyclonically to produce a well defined mass transport to the southeast along the continental slope.

The conclusion seems inescapable that at least during the spring of 1966 there was a quasi-steady subsurface countercurrent hugging the edge of the continental slope. The countercurrent appears to have disappeared or migrated further offshore by the middle of June (Figure IV-12). The hydrographic sections (Figures III-11 and III-12) made in October and November, 1965, do not suggest the existence of a well defined countercurrent close to the continental boundary.

6. Tidal and inertial currents. The tidal and inertial currents generally are small compared to steady currents over the entire boundary as demonstrated by Figures IV-2, IV-3 and comparisons between net drift vectors listed in Appendix D and tidal currents indicated in Figure IV-5. Combined tidal and inertial current speeds seldom exceed a few tenths of a meter per second even at the head of De Soto Canyon when the water is well stratified.

The tide and tidal currents are predominantly diurnal. Both tidal and inertial influence are apparent in surface layer motion over the shelf. Currents in the lower layer do not reveal clear tidal and inertial influence. There is a

lamentable lack of knowledge about the general propagation of the surface tide in the Gulf of Mexico. Significant internal tides have not been demonstrated except in the nearshore region.

B. The Quasi-steady Circulation

At this juncture, any discussion of the general quasi-steady circulatory regime in the northeast Gulf of Mexico must be largely conjectural. All evidence available indicates that the circulation is highly variable over spatial scales of the order of 100 kilometers and temporal spans exceeding a few weeks. Part of this apparent variability may be due to inadequacy of observations but the generalization should stand the test of time. The suggestion is advanced that the circulation in deeper water is the main driving influence for the quasi-steady circulation over the entire continental boundary. Major storms, fronts or hurricanes unquestionably introduce circulatory transients but their effect probably is confined mostly to the surface layer. Therefore, evaluation and predictability of the boundary circulation in the "instantaneous" sense as defined by Stommel (1965) implicitly depends on knowledge of currents in deep water, notably the loop current.

The general boundary flow is envisioned as a two-layer system separated by the seasonal thermocline and sharp transition above the salinity maximum. This density contrast between the two layers is sharpened over the shelf during the warmer months and virtually disappears in the winter, i.e., shelf waters are of the surface layer only. Bathymetry plays a controlling role in the boundary circulation.

1. Bathymetric influence. De Soto Canyon is the major topographic feature in the northeast Gulf boundary and its influence on horizontal circulation has been seen to be correspondingly great. Numerous modes of representing the field of flow and hydrographic variables have been employed elsewhere (Gaul and Boykin, 1964 and 1965) as well as in previous

illustrations; almost all reveal an obvious correlation with the bathymetry, especially in the vicinity of De Soto Canyon.

The quasi-steady currents, surface and subsurface, show a strong tendency to be aligned with the bottom topography. The previously suggested shear and mixing zone is oriented along the edge of the shelf. Not only can the slope of the boundary guide the currents and cause meanders in the manner suggested by Warren (1963) as is suggested in Figure V-3, for example, but abrupt changes in boundary orientation can cause a net transverse transport. This may be a controlling factor in the contrast in beach materials and water mass characteristics over the shelf east and west of De Soto Canyon.

2. Surface layer circulation. Streamlines of flow in the surface layer offshore from the continental margin appears to conform well with those of subsurface waters in the upper several hundred meters. Further evidence for this is the rapid transport of drift bottles from the northeast Gulf to the east Florida coast (Gaul and Boykin, 1964 and 1965). Current speeds at the surface generally are higher than at greater depths.

Surface currents over the boundary, particularly over the shelf in summer months, commonly deviate considerably from currents in the lower layer. Often surface and subsurface currents are in opposition. No generalization can be made as to relative magnitude of surface and subsurface currents, there being a strong dependence on time and location.

The main impact of the Mississippi River outflow on surface circulation is through an increase in density stratification. De Soto Canyon generally appears to be the eastward limit of intrusion of Mississippi River water except when major wind systems exert significant influence on the surface circulation. This suggests that there must be a net surface transport westward around the Mississippi delta that is confined to the shelf. Furthermore, the net surface circulation must sweep southeastward across the shelf between Pensacola

and Panama City to maintain the water clarity and high salinities so characteristic of the region.

3. Subsurface circulation. It is suggested that the subsurface (below the seasonal thermocline) circulation is altered only slightly by major disturbances acting at the air-sea interface. This implies that the subsurface boundary circulation is closely coupled, either directly or indirectly, with the influx of water through the Yucatan Channel and its intrusion northward. Variations in position or intensity of the loop current must be reflected in the subsurface boundary flow. The considerable variability of subsurface currents observed in the northeast Gulf are construed as indicative of corresponding fluctuations or geographic shifts in the loop current.

The subsurface circulation exhibits marked seasonal or shorter period changes. The regimes of October-December 1965 and March-June 1966 are strikingly dissimilar. Whether or not these conditions may be considered typical of late fall and spring is a moot point that must await more frequent observations distributed over one or more years.

Evidence is good that in November of 1965 transport along the periphery of the boundary was eastward and that the waters had moved from the Yucatan Channel to the vicinity of the Mississippi delta with only slight mixing. Hence, it is concluded that the loop was much further north than the position indicated in Figure V-1 or that a current filament had traversed the center of the Gulf. Measurements in 1965 and 1966 by Leipper (personal communication) suggest that such current filaments may be common; measurements by Nowlin and McLellan (1967) and by Nowlin and Reid (personal communication) taken in 1966 and illustrated in Figures V-1 and V-2 support the notion of a broad single gyre centered in the east Gulf.

Direct measurements in the spring of 1966 consistently indicate eastward subsurface flow. Figure V-1 places the northern limit of the loop current about 100 kilometers south

of the edge of the continental slope. Perhaps there was an east-west elliptical gyre just north of the loop of the sort indicated in Figure 21 of the paper by Nowlin and McLellan (1967) from observations made in the winter of 1962. Even if the observed countercurrent may have been narrow and adjacent to the boundary, the possibility of several additional flow features between it and the loop seems remote. Therefore, the current must be closely related to the loop.

Although a net transverse transport of subsurface water onshore occurs, the main transport tends to be closely aligned with the bottom topography. Current speeds over the continental slope are less than half of nominal loop current speeds but higher than found on the shelf. Thus, a lateral transfer and loss of energy at the boundary is indicated. This also supports the suggestion that the loop current is the main driving force for subsurface circulation over the continental margin.

C. Suggested Future Investigations

The range of worthwhile studies pertinent to circulation in the northeast Gulf of Mexico extends from theoretical investigation of shear flow in a stratified medium to direct monitoring of transport through the Yucatan Channel. Of primary importance to <u>all</u> investigations of circulation above 2000 meters in the <u>entire</u> Gulf of Mexico is extensive temporal and spatial description of the loop current system. This includes attention to the velocity structure of flow through the Yucatan Channel and Florida Straits. It is essential that surveys be highly synoptic and preferably supplemented by at least three fixed position monitoring stations; one each near the Yucatan Channel, Florida Straits and at a critical position on the left flank of northward flow of the loop current near the center of the Gulf. All hydrographic surveys should be accompanied by direct current observations extending to at least 500 meters.

One feature of flow along the northeast Gulf continental margin that deserves emphasis is the formation and characteristics of eddy systems over the continental slope. This might require establishment of fixed position current monitoring stations at, say, three locations along the 1000 meter isobath; one about 150 kilometers on each side of the axis of De Soto Canyon and one in the Canyon. These measurements should be supplemented by periodic hydrographic surveys of the sort conducted in 1963-1966 except that the area offshore from De Soto Canyon and westward to the delta should receive more attention. Nominal hydrographic station spacing of 20 kilometers is appropriate and the survey region must be covered within one week.

The greatest possible emphasis should be placed on temporal variability in any future observations of Gulf circulation. Measurements should be repeated at regular intervals. Time series of currents at almost any location in the Gulf would be useful in direct proportion to the availability of regional observations from which can be gained a notion of the spatial regime, hopefully at somewhat regular time intervals.

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APPENDIX A

HYDROGRAPHIC STATION COORDINATES

The tabulation below is of "standard" hydrographic station positions selected for repeated surveys of the northeast Gulf of Mexico. Nominal sounding depths are given together with geographic and loran coordinates.

Sta.	Depth (met.)	Latitude	Longitude	Loran (3H0)	Loran (3H1)
I	31	30°00.6'	85°54.2'	3694	2901
II	18	30°07.2'	85°46.5'	----	----
III	37	29°54.3'	86°01.4'	3683	2855
IV	366	29°22.0'	86°38.7'	3532	2535
V	366	29°28.1'	86°46.2'	3554	2453
VI	37	30°07.8'	86°26.0'	3683	2557
VIII	33	30°09.2'	86°55.5'	3664	2250
IX	366	29°30.8'	86°55.5'	3559	2350
X	18	29°28.4'	85°29.7'	3598	3210
XI	366	28°45.0'	86°19.4'	3303	2715
A1	1280	28°30.0'	88°46.5'	3303	1667
A2	1370	28°43.5'	88°26.3'	3350	1731
A4	1355	28°56.1'	88°04.3'	3397	1833
A6	1480	29°03.8'	87°43.7'	3430	1970
A8	1370	29°06.6'	87°30.6'	3444	2074
A11	915	29°11.4'	87°17.4'	3468	2181
A12	457	29°16.0'	86°45.5'	3500	2475
A13	550	29°10.0'	86°52.5'	3468	2418
A14	730	29°02.5'	87°01.2'	3428	2346
A15	915	28°54.4'	87°10.4'	3388	2278
A19	1830	28°36.7'	87°30.4'	3306	2150
A26	421	28°39.0'	86°26.4'	3269	2657
A27	550	28°32.8'	86°33.6'	3236	2598

Sta.	Depth (met.)	Latitude	Longitude	Loran (3H0)	(3H1)
A28	730	28°25.1'	86°42.3'	3197	2532
A29	915	28°19.2'	86°49.1'	3168	2482
A31	1830	28°13.2'	86°55.8'	3142	2436
A33	2834	28°08.1'	87°01.6'	3117	2395
A41	2435	28°23.3'	87°46.0'	3249	2063
D1	42	29°49.5'	86°06.9'	3670	2813
D2	52	29°44.5'	86°12.6'	3649	2768
D3	91	29°40.1'	86°18.0'	3627	2722
D4	152	29°34.1'	86°24.8'	3596	2660
D5	183	29°31.5'	86°27.7'	3584	2636
D6	229	29°28.0'	86°31.8'	3565	2597
D18	29	29°23.7'	85°35.1'	3562	3152
D19	55	29°19.2'	85°40.6'	3527	3091
D20	91	29°14.2'	85°46.3'	3491	3032
D21	183	29°08.2'	85°53.0'	3448	2963
D22	256	29°00.6'	86°01.9'	3398	2878
D23	280	28°57.4'	86°05.4'	3378	2846
D24	311	28°52.8'	86°10.7'	3348	2794
D25	238	29°02.5'	85°59.2'	3410	2900
D27	284	28°56.5'	86°06.2'	3372	2832
D29	329	28°50.5'	86°12.5'	3336	2776
G	915	28°50.7'	88°30.4'	3377	1675
G2	915	28°42.5'	88°55.2'	3349	1571
G4	915	28°47.4'	88°43.1'	3365	1614
G23	18	30°04.3'	87°43.7'	3619	1761
G24	33	29°47.0'	87°43.7'	3578	1820
G25	33	29°55.7'	87°43.7'	3602	1787
G26(R)	35	29°38.2'	87°43.7'	3552	1850
G27	55	29°30.8'	87°43.7'	3530	1876
G29	91	29°23.4'	87°43.7'	3505	1902
G31	366	29°16.6'	87°43.7'	3479	1927

Sta.	Depth (met.)	Latitude	Longitude	Loran (3H0)	Loran (3H1)
G33	915	29°12.0'	87°43.7'	3462	1942
K5	26	29°17.4'	85°06.8'	3388	3270
M59	205	28°38.3'	89°15.0'	3337	1499
M64	1005	28°24.0'	89°00.0'	3286	1623
M65	825	28°17.3'	89°15.0'	3267	1582
M93	550	28°31.0'	89°45.7'	3320	1417
M99	1095	28°10.0'	89°25.0'	3246	1568
T1	55	30°00.0'	86°30.0'	3670	2542
T3	91	29°52.0'	86°34.0'	3648	2523
T5	183	29°39.5'	86°40.2'	3603	2489
T12	29	30°12.3'	86°55.5'	3670	2241
T13	91	30°05.8'	86°55.5'	3658	2260
T14	128	30°00.9'	86°55.5'	3648	2273
T15	165	29°53.9'	86°55.5'	3634	2292
T17	183	29°47.9'	86°55.5'	3617	2309
T20	229	29°39.5'	86°55.5'	3591	2330
T27	366	29°27.9'	87°17.4'	3534	2137
T36	518	29°22.2'	86°54.0'	3526	2380
T37	730	29°17.0'	87°04.0'	3496	2295
27	3105	25°56.5'	86°39.0'	----	----
32A	3178	25°42.0'	89°38.5'	----	----
43	3076	27°12.0'	87°05.0'	----	----
56A	342	29°00.0'	86°16.0'	----	----
58	2378	28°32.0'	87°40.5'	----	----
59C	1070	28°37.9'	88°45.2'	3333	1641
61	750	27°46.5'	89°44.5'	----	----
101	494	29°19.4'	86°51.2'	3513	2410
102	1326	29°07.7'	87°30.4'	3448	2074
103	1463	29°00.6'	87°55.4'	3416	1886
104	1298	28°57.2'	88°06.9'	3402	1810
105	1179	28°54.1'	88°18.6'	3389	1741

Sta.	Depth (met.)	Latitude	Longitude	Loran (3H0)	Loran (3H1)
106	549	28°40.4'	89°04.8'	3343	1534
107	166	28°35.9'	89°25.0'	3331	1470
108	366	28°33.4'	89°36.2'	3325	1439
202	70	29°42.3'	86°15.3'	3639	2746
203	123	29°37.2'	86°21.2'	3613	2693
204	150	29°34.3'	86°24.5'	3599	2663
205	216	29°28.7'	86°31.0'	3569	2605
206	293	29°25.5'	86°34.6'	3552	2572
207	412	29°18.5'	86°42.7'	3513	2502
208	477	29°14.2'	86°47.5'	3490	2459

APPENDIX B

PERFORMANCE ANALYSIS OF THE STD SYSTEM

In this appendix an analysis is made of the performance characteristics, particularly in regard to measurement of salinity, of the salinity/temperature/depth (STD) system used for hydrographic casts in the northeast Gulf of Mexico from September 1965 to May 1966. The system is manufactured by the Hytech Products Division of the Bissett-Berman Corporation in San Diego, California, and is identified as Hytech Model 9006. The system design has evolved over a period of years from development work initiated at Woods Hole Oceanographic Institution (Hamon and Brown, 1958; Brown and Hamon, 1961) and subsequently extended by Brown (1963; 1964).

1. System Description

The underwater part of the STD (Figure B-1) consists of separate transducers for measurement of salinity, temperature and depth which are mounted in the lower section of a structural frame. The frequency modulated outputs from the transducers are multiplexed by a fourth underwater assembly which telemeters the three FM signals up the center conductor of the suspending cable and through slip rings mounted on the winch drum to a band pass filtering, signal conversion and recording system. Engineering characteristics of the system are given in various brochures issued by Bissett-Berman Corporation.

Depth measurement is by means of an open port strain gage pressure transducer. The temperature transducer is a pressure protected wire wound platinum resistance thermometer. The key assembly in the salinity transduction system is the inductively coupled conductivity sensor. Companion transducers and associated circuitry are built into the system to compensate for first and second order effects of temperature and pressure on

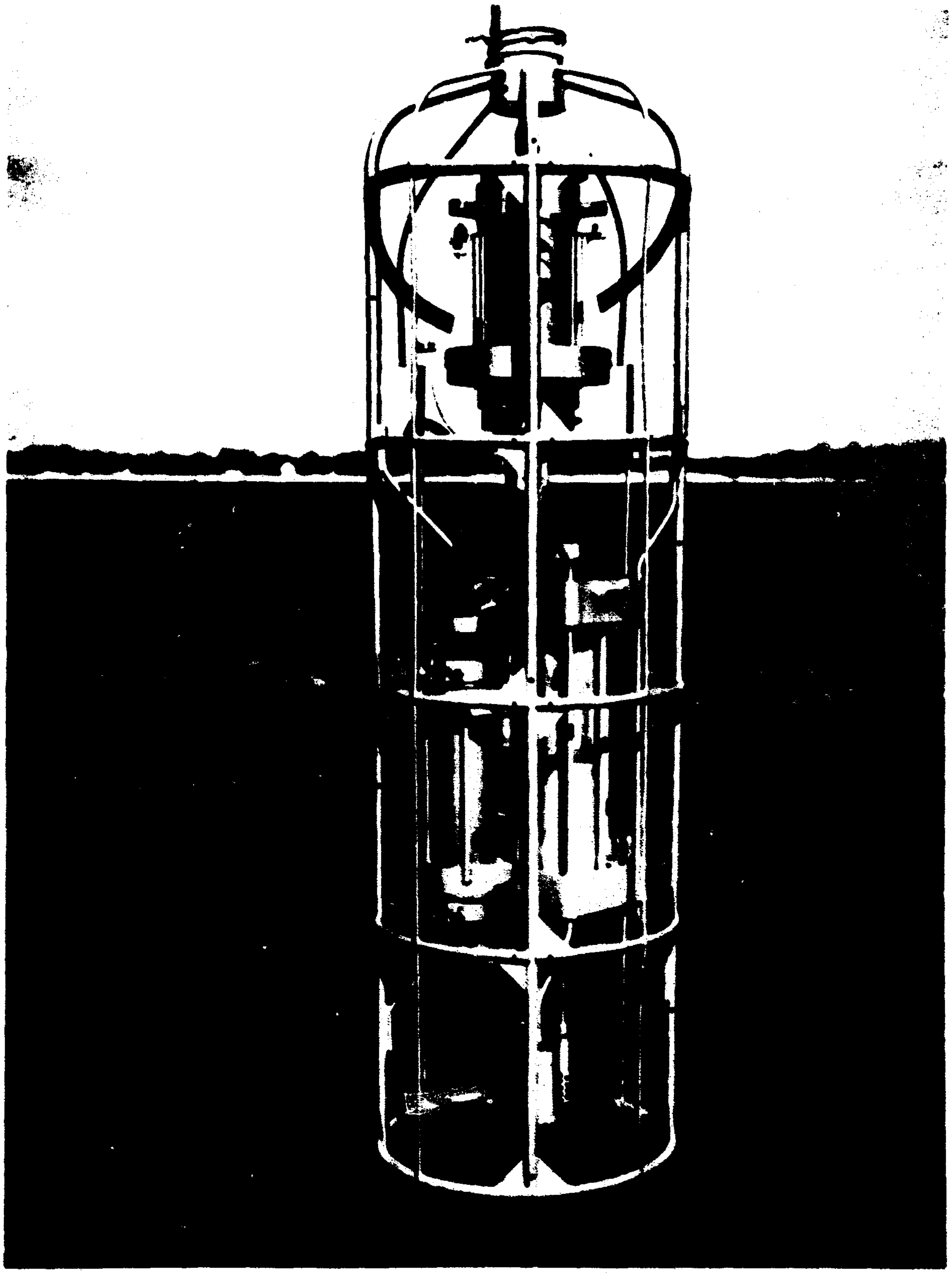

FIGURE B-1. Underwater part of the Hytech STD system.

conductivity such that the transduction system output is proportional to salinity. Design considerations and compensation techniques are given in detail by Brown (1964) together with error estimates after compensation. Some of the manufacturer furnished specifications for the STD are given in Table B-1. Values given are applicable to the recording ranges used in the northeast Gulf program and do not take into account chart reading errors.

TABLE B-1. STD system measurement specifications furnished by Bissett-Berman Corporation.

Parameter	Accuracy	Repeatability	Time Constant
Salinity	±0.03‰	±0.01‰	Variable
Temperature	±0.05°C	±0.01°C	0.3-0.4 sec.
Depth	±0.25% f.s.	±0.1% f.s.	~0.001 sec.

2. Factors Governing Performance

The discussion that follows hinges on the "variable" entry in Table B-1 for the salinity measurement time constant. The term "variable" refers to the differences in time constant between the several transducers in the salinity sensing system, viz., conductivity sensor and the temperature and pressure compensating probes. The electrical time constant of the conductivity probe and circuitry is of the order of 0.001 seconds. The effective conductivity measurement time constant may be significantly larger due to frictional and form modification of flow around the probe and through its core. It also should be noted that the conductivity measurement field is distributed over a sea water volume larger than the conductivity probe with the greatest influence being exerted by water within the core where restriction to flow is greatest. The first order temperature compensation probe, on

the other hand, has a nominal time constant of 0.35 seconds and is much smaller than the conductivity probe. Furthermore, the basic temperature measurement is related to the contact boundary consisting of the outside metal sheath of the probe and the frictional boundary layer of the fluid. It is noteworthy that the boundary layer itself may be the limiting factor in response of such a contact probe; preliminary laboratory tests indicate that only slightly less than 0.1 seconds may be achievable.

The accuracy specifications in Table B-1 are for the static case, i.e., no relative motion (in the macroscopic sense) between fluid and probe. The actual ocean, however, exhibits a wide range of vertical gradients of temperature and salinity. The effect of these gradients on indications from the underwater transducers depends upon the descent rate in relation to instrument time constants. An ideal STD system would have instantaneous response and identical detection volumes (spatial distribution functions) for each probe. Practical limitations are severe in relation to significantly changing probe configurations so the most promising area for improvement is in the time constants. The initial objective should be to match the time constants. This is extremely difficult with currently known transduction techniques. Paradoxically, the conductivity probe is large and has a short time constant relative to the temperature compensation probe which is small and has a long time constant. The analysis below is focused on the time constant mismatch but no account is taken of detection volume or fluid flow modification.

Before undertaking the analysis of salinity error, some other factors in system performance should be noted. The recorder used in the STD employs a pair of servo driven pens and a servo driven chart drive to produce separate traces of temperature and salinity versus depth on a prepared grid. Periodic calibrations are made in the field to establish full

scale (frequency dependent) end points on the grid for each of the parameters. The time constants of the servo drives depend on sensitivity adjustments which often are made in the field and probably have lower limits of the order of 0.1 seconds. From Table B-1 it is evident that the system should respond to depth changes more readily than temperature changes, perhaps by a factor of three or four. Changes in indicated (incorrectly compensated) salinity should be recorded with about the same response as depth changes. Thus, indicated temperature will lag indicated salinity, i.e., the temperature trace will be displaced downward for a descending cast. This discrepancy is not taken into account in the analysis below and was ignored in all reduction of northeast Gulf data since it generally appeared to be negligible within limits of descent rates and chart scales that were used.

Another interesting operational factor is that traditional oceanographic collection techniques have not required quantitative monitoring of cable lowering rates. Few winches are fitted with accurate line speed indicators and little attention normally is given to maintenance and calibration of indicators found aboard a ship. Considerable attention was devoted to calibration of line speeds for casts made in the northeast Gulf. Even so, the accuracy of fall rate estimates may not be much better than five per cent.

3. Salinity Error Induced by Temperature Gradient

Conductivity (specific conductance) is about an order of magnitude more dependent upon temperature than salinity. In the STD system a resistance thermometer probe ("identical" to but separate from the temperature measurement probe) is incorporated in the salinity sensing system to compensate for temperature effect on conductivity. A major difficulty arises from the previously mentioned time constant difference or mismatch. When the descending instrument encounters a vertical

thermal gradient, the apparent compensation "temperature" sensed by the resistance thermometer will be in error an amount dependent on the difference in time constants and the time rate of change of ambient temperature, i.e., the vertical temperature gradient and the descent rate.

For a specific temperature, T_o, it is convenient to define a conductivity ratio,

$$R(S) = \frac{G(S,T_o)}{G_o(S_o,T_o)} \tag{B-1}$$

where $G(S,T_o)$ is the conductivity of a sample of salinity, S, and $G_o(S_o,T_o)$ is the conductivity of a sample at a specified salinity. Brown and Allentoft (1966) have run extensive laboratory experiments to evaluate R(S) using reference values of $T_o = 15°C$ and $S_o = 35.000‰$. A least squares best fit to their empirical data yielded the relation

$$S = R(a + bR + cR^2) \tag{B-2}$$

where a = 29.958, b = 5.9039 and c = -0.8637. Equation (2) is considered to be within 0.2% over the ranges $30‰<S<40‰$ and $0°C<T<40°C$ where most of the error is related to temperature.

Consider the total differential of ambient conductivity,

$$dG(S,T) = \frac{\partial G}{\partial T}dT + \frac{\partial G}{\partial S}dS = 0 \tag{B-3}$$

or

$$\frac{dS}{dT} = -\frac{\partial G/\partial T}{\partial G/\partial S}. \tag{B-4}$$

Writing Equation (1) in the form

$$G(S,T) = R(S)G_o(T)$$

and taking partial derivatives gives

$$\frac{\partial G(S,T)}{\partial T} = R(S)\frac{dG_o(T)}{dT}$$

and

$$\frac{\partial G(S,T)}{\partial S} = \frac{\partial R(S)}{\partial S}G_o(T).$$

Substitution of the partials into Equation (4) yields

$$\frac{dS}{dT} = -\frac{R(S)}{R'(S)}\,\frac{1}{G_o(T)}\,\frac{dG_o(T)}{dT} = -K_G(T)\frac{R(S)}{R'(S)} \tag{B-5}$$

where the prime denotes partial differentiation with respect to the argument. Temperature dependence of the conductivity coefficient, K_G, is given in Figure B-2.

An explicit relation for R(S) may be obtained by inversion of Equation (2). This was accomplished by performing a least squares curve fit to points generated from Equation (2) to obtain

$$R(s) = \alpha + \beta S + \gamma S^2 \tag{B-6}$$

with $\alpha = 0.038011$, $\beta = 0.029435$ and $\gamma = -0.0000557$. Noting that the derivative of Equation (6) is

$$R'(S) = \alpha + 2\beta S + 3\gamma S^2 \tag{B-7}$$

it will be convenient to define a conductivity ratio coefficient,

$$K_R(S) = \frac{R(S)}{SR'(S)} = \frac{\alpha+\beta S+\gamma S^2}{\alpha+2\beta S+3\gamma S^2}. \tag{B-8}$$

Writing Equation (5) in differential form and taking the derivative with respect to time gives

$$\frac{dS}{dt} = -SK_R K_G \frac{\partial T}{\partial z}\,\frac{\partial z}{\partial t} = -SK_R K_G V\frac{\partial T}{\partial z} \tag{B-9}$$

where V is the instrument descent rate and z is directed positive downward. If (9) is written in difference form,

$$\Delta S_1 = -SK_R K_G V\frac{\partial T}{\partial z}\Delta\tau \tag{B-10}$$

then ΔS_1 may be interpreted as the salinity error caused by a time lag, $\Delta\tau$, of the temperature compensation thermal probe relative to the sensing of conductivity, G(S,T), by the toroidal conductivity probe.

The salinity error given by Equation (10) accounts only for the lag in response of the temperature compensation probe. There are a variety of other potential sources of error such as the response of the depth transducer which would lead to an

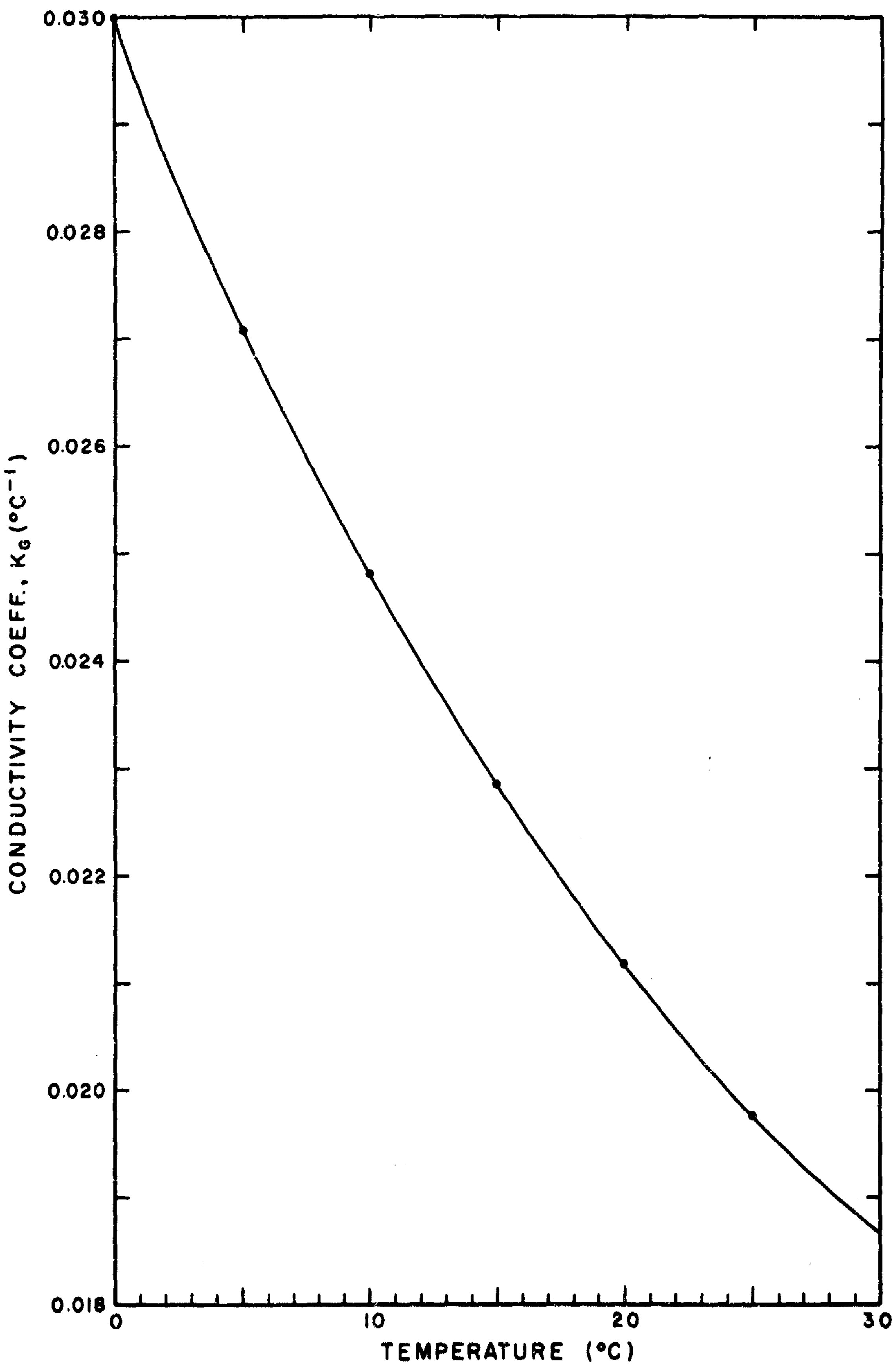

FIGURE B-2. Temperature dependence of the conductivity coefficient, K_G.

erroneous estimate of temperature gradient, the magnitude of which would be proportional to descent rate. Temperature effects on the conductivity toroid should certainly be extremely small but those on circuitry components could be significant. The components have been designed to operate within tolerances over the oceanic temperature range such that maximum salinity error will be 0.02‰. However, the additional error that might be caused by differential time response of the various components to large temperature changes is unknown. It seems safe to assume that these errors are one or more orders of magnitude smaller than that estimated by Equation (10).

4. Salinity Error Induced by Probe Separation

The STD underwater assembly initially delivered for use in the northeast Gulf was constructed such that the temperature compensation probe of the salinity sensor was located 0.15 meters above the center of the conductivity probe. Such a vertical separation placed the compensation probe in the wake of the conductivity probe. More importantly, in the presence of a vertical gradient the compensation probe was in contact with water having a different temperature than the water surrounding the conductivity probe. For a descending cast this simply added to the error caused by the slower response of the compensation probe. Neglecting effects of the wake and assuming a linear vertical gradient between probes, the salinity error induced by a probe separation, h, is

$$\Delta S_2 = -SK_R K_G h\frac{\partial T}{\partial z}. \qquad \text{(B-11)}$$

The STD system was modified after completion of field work in December 1965 such that the temperature compensation probe was mounted adjacent to and midway along the conductivity probe which is the configuration shown in Figure B-1.

5. The Salinity Correction Equation

The total error induced by time constant difference and probe separation is the sum of Equations (10) and (11),

$$\Delta S = \Delta S_1 + \Delta S_2 = -SK_R K_G \frac{\partial T}{\partial z}(V\Delta\tau + h). \qquad \text{(B-12)}$$

The corrected salinity, S, is

$$S = S^* + \Delta S \qquad \text{(B-13)}$$

where S* is the indicated salinity. If indicated salinity is substituted for actual salinity in Equation (12), the corrected salinity may be approximated from Equation (13) by

$$S \cong -S^*\left[1 - K_R K_G \frac{\partial T}{\partial z}(V\Delta\tau + h)\right]. \qquad \text{(B-14)}$$

To test the suitability of Equation (14) for practical application, consider the following parameter values: $h = 0$, $V = 2$ meters per second, $\Delta\tau = 0.35$ second, $\partial T/\partial z = 1°C$ per meter, $S = 35‰$ and $T = 20°C$. From Figure B-2, $K_G = 0.0212$. From Equation (8), $K_R = 0.5280$. Substitution into (10) gives a salinity error of $\Delta S = 0.274‰$. From (13), the indicated salinity is $S^* = 34.726‰$. Using this value in (10) gives a salinity error of $\Delta S^* = 0.274$, i.e., the computed salinity error is unaffected to the third decimal place by choice of actual or indicated salinity. This behavior will pertain over a practical working range of salinity, say 32‰ to 37‰, for temperature gradients of the order chosen for this example because of the relatively insignificant variation of $K_R(S)$.

APPENDIX C

SUMMARY OF BATHYTHERMOGRAPH CASTS AND WATER SAMPLE COLLECTIONS OFF PANAMA CITY

The summary below is of time periods in 1963-1965 during which BT casts and water sample collections were made along the transect off Panama City. The stations at each end of a particular run are shown together with the total number of stations occupied. The unspecified stations are tabulated in Appendix A and are those shown in Figure III-1. Surface ("sfc.") water samples were collected at a nominal depth of one meter below the free water surface. "Max." denotes water sample collection at the maximum depth to which the BT descended. Complete tabulations of the data are given by Gaul and Boykin (1964; 1965) and Gaul, Boykin and Letzring (1966).

Starting Time and Date	Elapsed Time (hrs.)	Terminal Stas. Shallow	Terminal Stas. Deep	No. of Stas.	Water Sample Depths
1010/08May63	5.5	II	IV	8	Sfc., Max.
0230/10May63	6.2	II	IV	8	Sfc., Max.
1435/27May63	8.0	II	IV	8	Sfc., Max.
1020/28May63	5.2	II	IV	8	Sfc., Max.
2240/29May63	5.5	II	IV	8	Sfc., Max.
1900/27June63	5.5	II	IV	8	Sfc., Max.
1220/01July63	5.7	II	IV	8	Sfc., Max.
0515/07Aug63	9.7	II	IV	8	Sfc., Max.
1115/05Sep63	5.7	II	IV	8	Sfc., Max., 120m.
0500/03Jan64	9.0	II	IV	9	Sfc., Max., 90m.
0815/10Apr64	11.5	II	A15	10	Sfc.,Max.,50, 150,250m.

Starting Time and Date	Elapsed Time (hrs.)	Terminal Stas. Shallow	Deep	No. of Stas.	Water Sample Depths
1000/07May64	13.7	II	A13	10	Sfc.,Max.,50, 150,250m.
1150/29June64	14.5	II	A15	10	Sfc.,Max.,50, 150,250m.
1400/03July64	6.0	II	A15	10	Sfc.,Max.,50, 150,250m.
0840/03Aug64	8.7	II	A13	9	Sfc.,Max.,50, 150,250m.
0835/31Aug64	10.0	II	A13	11	Sfc.,Max.,50, 150,250m.
1015/17Oct64	5.0	II	D4	7	Sfc., Max., 50,150m.
2150/18Oct64	4.2	II	D4	6	Sfc., Max., 50,150m.
0840/02Nov64	9.2	II	A13	11	Sfc.,Max.,15, 35,75,100, 175,250m.
1325/06Nov64	3.7	II	D3	7	Sfc., Max., 15,35,75m.
0820/15Dec64	11.2	II	A13	11	Sfc.,Max.,15, 35,75,100, 175,250m.
1310/05Jan65	8.5	II	IV	10	Sfc.,Max.,15, 35,75,100, 175,250m.
2140/05Jan65	6.7	II	IV	10	Sfc.,Max.,15, 35,75,100, 175,250m.
0700/03Mar65	10.0	II	A13	11	Sfc.,Max.,15, 35,75,100, 175,250m.
1320/23Mar65	17.2	II	A13	10	Sfc.,Max.,15, 35,75,100, 175,250m.
0920/05Apr65	8.5	M4	A13	10	Sfc.,Max.,15, 35,75,100, 175,250m.
1210/09Apr65	4.0	II	D3	7	Sfc.,Max., 15,35,75m.

Starting Time and Date	Elapsed Time (hrs.)	Terminal Stas. Shallow	Terminal Stas. Deep	No. of Stas.	Water Sample Depths
0835/10May65	9.2	II	A13	11	Sfc.,Max.,15, 35,75,100, 175,250m.
0905/19May65	10.7	II	A13	11	Sfc.,Max.,15, 35,75,100, 175,250m.
1945/19May65	10.2	II	A13	12	Sfc.,Max.,15, 35,75,100, 175,250m.
0855/01June65	10.7	II	IV	10	Sfc.,Max.,15, 35,75,100, 175,250m.
1950/02June65	6.5	II	IV	10	Sfc.,Max.,15, 35,75,100, 175,250m.
0830/08June65	11.0	II	A13	11	Sfc.,Max.,15, 35,75,100, 175,250m.
1610/09June65	9.5	II	A13	11	Sfc.,Max.,15, 35,75,100, 175,250m.
0845/22June65	12.2	II	A15	12	Sfc.,Max.,15, 35,75,100, 175,250m.
0900/12July65	7.5	II	IV	9	Sfc.,Max.,15, 35,75,100, 175,250m.
1635/12July65	4.2	II	IV	10	Sfc.,Max.,15, 35,75,100, 175,250m.
1920/22July65	3.7	II	D3	7	Sfc.,Max., 15,35,75m.
0830/16Aug65	15.7	II	A15	13	Sfc.,Max.,15, 35,75,100, 175,250m.
1115/20Aug65	8.5	II	IV	10	Sfc.,Max.,15, 35,75,100, 175,250m.
1630/24Aug65	9.7	II	A15	13	Sfc.,Max.,15, 35,75,100, 175,250m.

APPENDIX D

SUMMARY OF NET DRIFT VECTORS

Given below is a tabulation of net drift speed and direction as calculated from direct current measurements made during 1963-1966. Three techniques were used: parachute drogues (PD), tethered drogues (TD) and Savonius rotors with direction vanes (SR) suspended on a "taut" mooring. Net drift is included for a limited number of the current measurements made at the deeper platform off Panama City (Stage I).

The time span over which the net drift was taken is shown as "drift period" beginning at the indicated "start time." "Obs. depth" refers either to the length of wire connecting the parachute or current cross to the surface float or the nominal depth of the rotor-vane assembly below the water surface.

Station and Method	Starting Date	Start Time (CST)	Drift Period (hrs.)	Obs. Depth (m.)	Drift Speed (mps)	Drift Dir. (°M)
VIII(TD)	8MAY63	2200	22.0	1	0.12	120
VIII(TD)	8MAY63	2200	22.0	15	0.12	075
VIII(TD)	8MAY63	2200	22.0	30	0.26	085
R(TD)	9MAY63	0200	21.0	1	0.03	125
R(TD)	9MAY63	0200	13.0	15	0.07	115
R(TD)	9MAY63	0200	21.0	30	0.09	085
VIII(TD)	30MAY63	0200	22.0	1	0.06	030
VIII(TD)	30MAY63	0200	22.0	15	0.07	045
VIII(TD)	30MAY63	0400	20.0	30	0.03	060
VIII(TD)	30MAY63	1100	24.0	1	0.08	165
VIII(TD)	30MAY63	1100	24.0	15	0.17	085
VIII(TD)	30MAY63	1300	22.0	30	0.21	070
R(TD)	30MAY63	1200	5.0	1	0.45	215
R(TD)	30MAY63	1200	5.0	15	0.08	200

Station and Method	Starting Date	Start Time (CST)	Drift Period (hrs.)	Obs. Depth (m.)	Drift Speed (mps)	Drift Dir. (°M)
G15(TD)	31MAY63	1000	16.0	1	0.18	095
G15(TD)	31MAY63	1000	12.0	15	0.23	095
G15(SR)	31MAY63	0900	14.0	15	0.33	100
44(SR)	30JUN63	0800	23.0	6	0.06	195
VIII(TD)	2JUL64	1400	16.0	1	0.12	120
VIII(TD)	2JUL64	1400	17.0	15	0.11	160
VIII(TD)	2JUL64	1400	16.0	30	0.08	180
I(SR)	6AUG64	0200	48.0	6	0.08	310
I(SR)	6AUG64	0200	48.0	30	0.02	160
VIII(TD)	6AUG64	1100	24.0	1	0.11	290
VIII(TD)	6AUG64	1100	24.0	15	0.13	295
VIII(TD)	6AUG64	1100	24.0	30	0.09	255
VIII(TD)	3SEP64	0800	21.0	1	0.15	070
VIII(TD)	3SEP64	0800	23.0	15	0.07	085
VIII(TD)	3SEP64	0800	23.0	30	0.01	340
VIII(TD)	5NOV64	1400	17.0	1	0.02	040
VIII(TD)	8APR65	0700	23.0	1	0.29	095
VIII(TD)	8APR65	0700	21.0	15	0.13	060
VIII(TD)	8APR65	0800	20.0	30	0.15	055
D3(PD)	21APR65	1700	12.0	10	0.25	160
D3(PD)	21APR65	1700	6.0	50	0.32	135
D3(PD)	21APR65	1700	13.0	100	0.06	350
D3(PD)	5MAY65	1230	16.5	4	0.04	150
D3(PD)	5MAY65	1300	16.5	40	0.06	290
D5(PD)	20MAY65	0145	22.5	10	0.12	140
D5(PD)	20MAY65	0145	22.5	75	0.23	165
D5(PD)	20MAY65	0145	23.5	150	0.04	140
D5(PD)	1JUN65	1730	14.5	20	0.08	305
D5(PD)	1JUN65	1730	24.5	130	0.07	140
D5(PD)	1JUN65	1730	11.5	170	0.06	135

Station and Method	Starting Date	Start Time (CST)	Drift Period (hrs.)	Obs. Depth (m.)	Drift Speed (mps)	Drift Dir. (°M)
T13(PD)	25JUN65	0600	20.5	3	0.04	300
T13(PD)	25JUN65	0600	20.0	20	0.07	200
IV(PD)	12JUL65	1930	16.5	8	0.05	060
IV(PD)	12JUL65	1930	17.5	150	0.07	100
IV(PD)	12JUL65	1930	17.5	300	0.06	090
VIII(PD)	21JUL65	2000	15.5	3	0.34	265
VIII(PD)	21JUL65	2000	10.0	13	0.43	265
VIII(PD)	21JUL65	2000	16.5	20	0.19	245
I(SR)	16AUG65	0400	48.0	6	0.05	155
I(SR)	16AUG65	0400	48.0	30	0.03	105
T27(PD)	20AUG65	2230	7.5	4	0.33	025
T13(PD)	21AUG65	1430	3.5	4	<0.01	---
G31(PD)	23AUG65	2000	6.5	10	0.43	275
G31(PD)	23AUG65	2000	6.5	250	0.50	250
A15(PD)	24AUG65	1000	6.0	10	0.06	060
A15(PD)	24AUG65	1100	5.0	250	<0.01	---
K21(PD)	17SEP65	0015	8.0	10	0.52	135
K21(PD)	17SEP65	0015	9.0	275	0.15	225
I(SR)	20SEP65	1200	48.0	6	0.08	085
I(SR)	20SEP65	1200	48.0	30	0.06	315
D3(PD)	21SEP65	0215	2.5	4	0.37	235
D3(PD)	21SEP65	0225	11.5	60	0.16	180
I(SR)	10MAR66	1400	24.0	6	0.18	345
I(SR)	10MAR66	1400	24.0	30	0.06	050
203(PD)	11MAR66	1915	12.0	10	0.56	080
203(PD)	11MAR66	1915	12.0	300	0.33	325
I(SR)	14MAR66	1300	24.0	6	0.17	025
I(SR)	14MAR66	1300	24.0	30	0.03	315
IV(PD)	22MAR66	0100	19.0	10	0.20	085
IV(PD)	22MAR66	0100	19.0	125	0.11	090

Station and Method	Starting Date	Start Time (CST)	Drift Period (hrs.)	Obs. Depth (m.)	Drift Speed (mps)	Drift Dir. (°M)
I(SR)	25MAR66	0300	48.0	6	0.16	150
I(SR)	25MAR66	0300	48.0	30	0.08	250
D5(PD)	26MAR66	0000	12.0	10	0.70	160
D5(PD)	26MAR66	0000	12.0	150	0.21	150
A15(PD)	26MAR66	0100	21.0	10	0.33	330
A15(PD)	26MAR66	0100	21.0	150	0.21	315
A15(PD)	26MAR66	0100	21.0	500	0.17	325
I(SR)	29MAR66	1600	24.0	6	0.11	160
I(SR)	29MAR66	1600	24.0	30	0.03	090
IX(PD)	31MAR66	1700	5.0	10	0.40	080
IX(PD)	31MAR66	1700	5.0	100	0.40	085
IX(PD)	31MAR66	1700	5.0	250	0.10	130
D5(PD)	15APR66	0330	4.0	10	0.33	130
D5(PD)	15APR66	0400	3.0	150	0.10	155
I(SR)	15APR66	0500	24.0	6	0.16	165
I(SR)	15APR66	0500	24.0	30	0.04	290
GS(PD)	15APR66	0930	8.5	150	0.11	335
A13(PD)	15APR66	1200	24.0	10	0.15	010
A13(PD)	15APR66	1200	24.0	150	0.03	060
A13(PD)	15APR66	1200	24.0	500	<0.01	---
A19*(PD)	15APR66	1100	20.0	10	0.64	030
A19*(PD)	15APR66	1100	20.0	150	0.47	030
A19*(PD)	15APR66	1100	20.0	500	0.35	030
D5(PD)	16APR66	0405	10.0	10	0.23	150
D5(PD)	16APR66	0405	10.0	150	0.04	145
GS(PD)	16APR66	0800	8.5	150	0.09	355
D1(PD)	25APR66	0025	45.0	30	0.16	330
D2(PD)	25APR66	0130	34.5	30	0.17	335
D3(PD)	25APR66	0240	17.5	30	0.07	330
D5(PD)	25APR66	0430	13.0	30	0.05	325
D5(PD)	25APR66	0430	12.0	150	0.03	325

Station and Method	Starting Date	Start Time (CST)	Drift Period (hrs.)	Obs. Depth (m.)	Drift Speed (mps)	Drift Dir. (°M)
IV(PD)	25APR66	1215	18.5	30	0.10	260
IV(PD)	25APR66	1215	36.0	150	0.06	320
A13(PD)	25APR66	1530	23.5	30	0.13	305
A13(PD)	25APR66	1530	23.0	150	0.08	335
IX(PD)	25APR66	1850	23.0	30	0.07	030
IX(PD)	28APR66	1830	40.0	150	0.06	265
D2(PD)	29APR66	1230	15.0	30	0.07	350
D3(PD)	29APR66	1350	13.0	30	0.13	285
I(SR)	29APR66	1400	48.0	6	0.02	020
I(SR)	29APR66	1400	48.0	30	0.01	040
D5(PD)	29APR66	1730	23.5	30	0.09	285
D5(PD)	29APR66	1800	22.0	150	0.11	345
IV(PD)	30APR66	0730	30.5	150	0.07	220
III(PD)	2JUN66	1200	28.0	15	0.12	250
D3(PD)	2JUN66	1030	33.0	15	0.19	135
D5(PD)	2JUN66	0930	35.5	15	0.26	130
IV(PD)	2JUN66	0800	39.0	15	0.12	155
IV(PD)	2JUN66	0800	39.0	150	0.19	135
A15(PD)	2JUN66	0400	49.0	15	0.14	335
A15(PD)	2JUN66	0400	49.0	150	0.12	325
A15(PD)	2JUN66	0400	49.0	300	0.09	310
A13(PD)	2JUN66	0600	45.0	15	0.05	220
A13(PD)	2JUN66	0600	45.0	150	0.06	250
K5(PD)	6JUN66	1430	22.5	15	0.10	310
A41(PD)	15JUN66	0800	49.5	15	0.05	290
A41(PD)	15JUN66	0800	49.5	150	0.04	240
A41(PD)	15JUN66	0800	49.5	300	0.03	240
A19(PD)	15JUN66	1000	44.5	15	0.05	355
A19(PD)	15JUN66	1000	44.5	150	<0.01	---
A19(PD)	15JUN66	1000	44.5	300	0.06	020

Station and Method	Starting Date	Start Time (CST)	Drift Period (hrs.)	Obs. Depth (m.)	Drift Speed (mps)	Drift Dir. (°M)
A15(PD)	15JUN66	1300	37.0	15	0.17	085
A15(PD)	15JUN66	1300	37.0	150	0.12	080
A15(PD)	15JUN66	1300	37.0	300	0.08	095
A13(PD)	15JUN66	1500	32.0	15	0.30	115
A13(PD)	15JUN66	1500	32.0	150	0.12	115
IV(PD)	15JUN66	1700	28.0	15	0.15	100
T17(PD)	15JUN66	1940	22.5	15	0.14	070
59C(PD)	17JUN66	1900	12.0	15	0.20	060
59C(PD)	17JUN66	1900	12.5	150	0.16	015
D1(PD)	27JUN66	1945	36.0	15	0.11	270
D2(PD)	28JUN66	0900	22.0	15	0.06	320
D2(PD)	28JUN66	0930	21.5	30	0.11	275
D3(PD)	28JUN66	1130	18.5	5	0.04	340
D3(PD)	28JUN66	1130	15.0	15	0.25	175
D3(PD)	28JUN66	1130	15.5	30	0.19	180
D3(PD)	28JUN66	1725	11.5	70	<0.01	---
D5(PD)	28JUN66	0020	26.0	30	0.14	110

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13. ABSTRACT

The quasi-steady ocean circulation over the continental margin of the northeast Gulf of Mexico ~~has been~~ surmised on the basis of three years of hydrographic and direct current observations. Observations were made by a wide range of techniques at two fixed platforms in the nearshore region off Panama City, Florida, and from small vessels during periodic surveys conducted over a larger area. Special attention has been given to the accuracy of measurements and to the temporal and spatial distribution of sampling relative to scales of observed circulatory phenomena.

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